Pentaquarks: Do They Exist?

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Recently there has been great excitement about the possible existence of pentaquarks. In this article, we will discuss the quark model and multiquark structures as well as the recent experiments carried out to study the existence of pentaquarks.

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Introduction

Since ancient times, human beings have been addressing the question of the composition of matter at the most fundamental level. The Greek philosophers Leucippus and Democritus proposed that all matter is made up of atoms (Greek meaning is 'uncuttable') and empty space. The discovery of the electron by J J Thomson, of the nucleus by E Rutherford and the neutron by J Chadwick changed the perception of the atom from 'uncuttable' to 'breakable.' The picture of the atom in the 1940's was that of protons, neutrons and electrons. They were considered to be the fundamental particles. However, the picture changed in the 1960's by the introduction, among other things, of the 'quark model,' which will be discussed below.

While the electron, muon, τ-lepton, and their corresponding neutrinos and their antiparticles are considered to be one set of fundamental particles that can be observed experimentally, called leptons, all other matter, hadrons, are assumed to be made up of another set of fundamental particles called quarks. These quarks cannot be observed as separate entities, as they are 'confined' in hadronic matter (for a recent discussion on properties of the strong interaction theory which won the Nobel Prize in Physics for the year 2004, see [1]). The theory which describes the interaction of these quarks via the exchange of 'gluons' is called quantum chromodynamics (QCD). According to the quark model there are six types of 'coloured' quarks (and their corresponding anti-quarks. They come in three colours). According to QCD all the hadrons are colourless combinations of quarks. Hadrons are further classified into 'baryons' and 'mesons.' Mesons are made up of a quark and an anti-quark while baryons are made up of three quarks. For instance protons and neutrons are baryons while pions (π mesons), Kaons and the η are mesons (see *Box* 1). Even though QCD allows for all kinds of colourless combinations, until now all the observed particles were either mesons or baryons. There was no experimental evidence for particles made up of four or more quarks or anti-quarks or combinations thereof allowed by QCD. Today, it is still impossible to solve the dynamics of QCD. Hence, one appeals to models which simplify the theory and provide some insight into the (particle) spectrum of QCD.

One theoretical model was considered by three Russian physicists D Diakonov, V Petrov and M Polyakov (DPP) in 1997, which predicted ten exotic states that could not be constructed from only three quarks. These states would correspond to those made up of four quarks and one anti-quark, which is an example of a pentaquark. Their work was based on an effective field theory proposed by T Skyrme in 1962, in which the nucleons are 'solitons' (see *Box* 2).

In the past, some symmetry properties of strong interaction dynamics were exploited to predict the existence of hitherto unknown states. For instance, in 1961, based on the SU(3) symmetry group[1], M Gell-Mann and Y Ne'eman independently proposed a model in which baryons and mesons were arranged in geometrical patterns in a two-dimensional plot. For instance, *Figure* 1 shows the patterns formed by the spin $\frac{3}{2}$ and spin $\frac{1}{2}$ baryons, and are named after their respective

SU(3) stands for 3×3 unimodular unitary matrices. Such matrices form a 'group' under matrix multiplication, which is a precise mathematical expression of an underlying symmetry. In this case, this (approximate) symmetry is the one enjoyed by the so-called strong interaction Hamiltonian describing the 3 lightest quark degrees of freedom, the detailed description of which is beyond the scope of this article.

Box 1. Quarks, Baryons and Mesons

Quarks are spin-1/2 particles that come in six flavors : up(u), down(d), charm(c), strange(s), top(t), and bottom(b). The u, c, and t quarks have a charge of +2e/3 and the d, s, and b quarks have a charge of −e/3. Reversing the sign of the charge we get the charge of the corresponding anti-quark. Each (anti-)quark comes in three (anti-)colors. Here the word 'color' denotes one particular quantum number of the quarks. It is an intrinsic property of the quark, just like its charge or spin. It is the property responsible for the strong interaction between the quarks. Assigning the color as red, blue or green to the quarks suggests a nice property of the quark combinations found in the nature. All naturally occurring particles are colorless. By colorless, we mean that either the total amount of each color is zero (for example, red and anti-red combination implies zero color) or the three colors are present in equal proportions. Every three-quark combination is given the name baryon (for example protons, neutrons) and a quark, anti-quark combination is called meson (for example pion, Kaon). For instance, a proton is made up of u, u, and d quarks while K^+ is made up of u and anti-s quarks (Kaons come in four types, K^+, K^-, K^0 and $\bar{K}^0$). Each quark is assigned a baryon number 1/3, while the anti-quark is assigned −1/3. Therefore the baryon number of a baryon is 1 while that of a meson is 0. Note that a baryon can have spin 3/2 or 1/2 and simplest meson spin 0 or 1.

All except the u quark (which is the lightest of all quarks) are unstable particles, due to the fact that the weak interaction which is always present, leads to their decay. For instance, one of the d quarks in the neutron can decay to a u quark, thereby changing the neutron into a proton, and also simultaneously emitting an electron and an anti-neutrino. Neutrons inside stable nuclei do not decay because of kinematic constraints. In the early days, cosmic rays, i.e., high energy particles from extraterrestrial sources were the only source of information on high energy particle reactions. Cosmic ray experiments showed all kinds of 'strange' events, where particles produced in pairs lived for a relatively long time, compared to what one expected. This was explained by Gell-Mann and A Pais by introducing particles which had 'strange' constituents.Today we know that these strange particles contain strange quarks, which subsequently decay. These strange particles were assigned a new quantum number called 'strangeness'. All these quantum numbers are useful in analyzing and constraining reactions. When the quark model was proposed in 1964 only the 3 lightest quarks, u, d and s were known. In later laboratory experiments as technology improved, the existence of charm, bottom and top quarks was proved.

multiplicities (i.e. decuplet has ten members and octet has eight members). Based on this model Gell–Mann predicted the existence of a particle that was necessary to complete the spin $\frac{3}{2}$ decuplet. In 1964, the famous bubble chamber experiment at Brookhaven confirmed the existence of such a particle. Now that particle is known as Ω^-, which is at the bottom of the decuplet

Box 2. Solitons

The idea of a 'soliton' came from the discovery of solitary water waves by Scott Russell in 1834. Russell, from Glasgow, was a businessman with a scientific temperament. While testing his boats on union canal near Edinburgh in August 1834, he saw a boat suddenly coming to a halt and the bow wave generated kept moving without losing speed. He thought there was something special and decided to follow the wave on horseback. He chased it for over a mile till it started to weaken. Russell realised this was not a wave of the type described by Bernoulli and Newton. He later conducted many experiments and studied them extensively. Typically, such solitary waves arise due to the non-linearity in the medium in which the wave propagates. A similar localized stable solution arises in quantum field theory, when non-linear terms exist in the corresponding field equations, and goes by the generic name of a soliton.

arrangement. In those days, this arrangement was compared with Mendeleev's periodic table. Mesons and quarks also form similar patterns; an example for mesons is shown in *Figure* 2 (a) while the arrangement for the lightest quarks in *Figure* 2 (b).

Theoretical Prediction of Pentaquarks

Using their model DPP predicted a model similar to that of baryons and mesons for pentaquarks. They

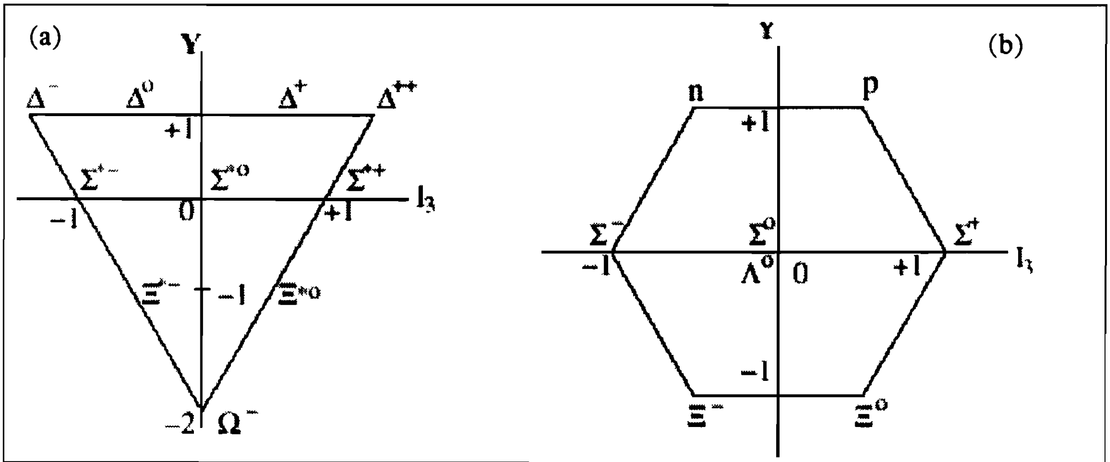

Figure 1. (a) The decuplet of spin 3/2 baryons and (b) The octet of spin 1/2 baryons. Here 'Y' represents Hypercharge which is the sum of baryon number and strangeness (Y=B+S) and 'I_3' represents the 3rd component of the 'isospin'. (Isospin symmetry is one which views the proton and neutron effectively as isospin up and isospin down states of a hypothetical isospin 1/2 particle.) We refrain from giving information on the other particles depicted on these plots in the interests of brevity.

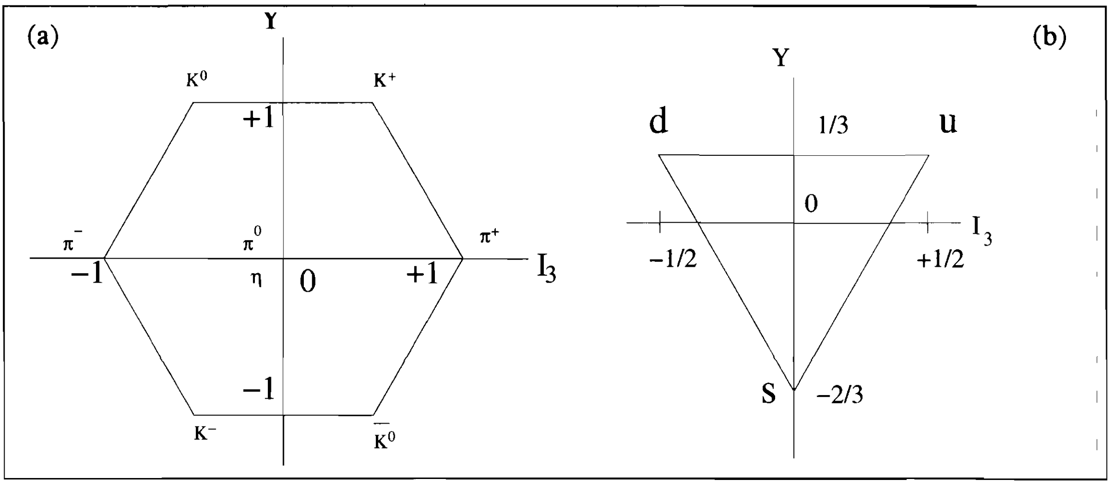

Figure 2.(a) The octet of lightest spin 0 mesons and (b) the pattern for the lightest quarks.

suggested that the two lowest 'rotational states' found in their model are the octet and the decuplet of baryons, while the next rotational level of solitons is the anti-decuplet of 'pentaquarks' with spin $\frac{1}{2}$ (see *Figure* 3).

In their paper they also predicted the masses for four pentaquarks. Every model requires some input parameter(s) to get useful predictions. In this model they assumed the mass of one of the nucleon-like members of this decuplet called 'N^*' to be 1710 MeV/c^2. This paper was the main motivation for the SPring-8 group in Japan, which claimed the first experimental observation of pentaquarks.

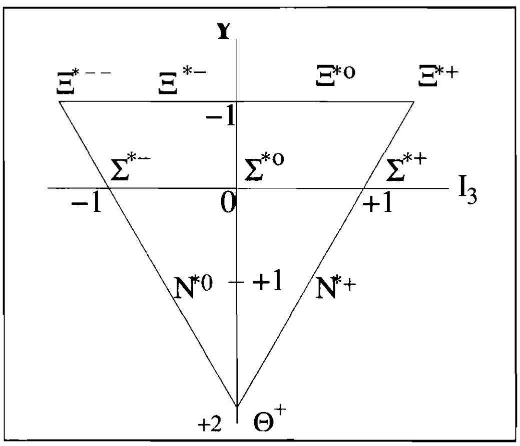

Figure 3. The anti-decuplet of pentaquarks predicted by DPP.

There are also other models which predict the existence of pentaquarks. Some of the models are based on diquark-diquark or diquark-triquark formation. In these models the five quarks are reconfigured into groups of two or three quarks (like ud and uds or ud, ud and s). Note that these groups are not the mesons and baryons, they are 'coloured' ones. Because of the colour-magnetic interaction these groups bind together firmly to form pentaquarks. These models are generally known as correlated quarks models. Even though all these models predict the existence of pentaquarks their prediction of masses of these particles are not mutually consistent. (An advanced reader may wish to consult [2] for theoretical models.)

Experimental Evidences for Pentaquarks

The pentaquark that many laboratories identified, was the 'Θ^+' pentaquark. The experimental observations say that this particle should consist of five quarks: two u quarks, two d quarks and one anti-s quark. The LEPS group at the SPring-8 facility in Harima, Japan, performed an experiment in which a high energy photon was fired at a carbon nucleus. Here there are two possibilities, one in which the photon can hit a proton and other one in which it can hit a neutron. The first reaction will be

$$\gamma p \rightarrow K^+ + \Lambda^* \rightarrow K^+ + K^- + p, \qquad (1)$$

where the p stands for a proton in the carbon nuclear target, and the Λ^* is the already known particle of mass $1520\,\mathrm{MeV}/c^2$. The other reaction would be

$$\gamma n \rightarrow K^- + \Theta^+ \rightarrow K^- + K^+ + n, \qquad (2)$$

where the n stands for a neutron in the carbon nuclear target, and the Θ^+ in the first stage of the reaction is a pentaquark (for a related discussion, see *Box* 3). They plotted the missing mass of both K^+ and K^- which

Box 3. Particle Detection

With sufficiently good detectors, by analyzing the tracks of the debris (final product particles) of the reactions, one can identify the particles that were created in the collision process and using conservation of energy, momentum, charge, baryon number, strangeness etc., one can assign properties such as mass-energy, charge etc., for the intermediate particle. Thus experimentalists reconstruct the entire reaction. They plot graphs that will show how energy changes with number of events. If any intermediate particle is formed then it will give a hump in the data.

Let us consider a high energy reaction

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n$$

If we plot the energy of all possible pairs of end products (like $\pi^+ n$, $\pi^- n$, $\pi^+\pi^-$) with the number of events in which they were observed with that energy, we will get a peak in the $\pi^+\pi^-$ case. Even if we plot the 'missing mass' of the neutron, we can get the same peak. In other cases there will not be any significant peak. It shows that the π^+ and π^- are formed from an intermediate particle. That particle is known as ρ^0 particle. The complete reaction is as below.

$$\pi^- + p \rightarrow \rho^0 + n \rightarrow \pi^+ + \pi^- + n,$$

Thus we are able to indentify the intermediate particles. For a more technical discussion, see, e.g.[4].

are shown in *Figure* 4. In both cases, care should be taken to avoid K^+ and K^- particles from other reactions. For Θ^+ spectrum, in order to avoid the K^- particles from the first reaction LEPS rejected the events in which they observed a proton (this is an example of a 'cut' in high energy experiments). From the plot they observed a peak at 1540 MeV/c^2 which corresponds to the mass of intermediate particle (DPP predicted a mass of 1530 MeV/c^2 for this particle). All the strong interactions including the two above, which involve only hadrons, should conserve strangeness and baryon number. From these conservation laws we come to know that the intermediate particle should have strangeness +1, baryon number +1 and charge +1. This combination of quantum numbers cannot be obtained using only two or three quark combinations. It requires five quarks; two u quarks, two d quarks, one anti-s quark. Thus a particle

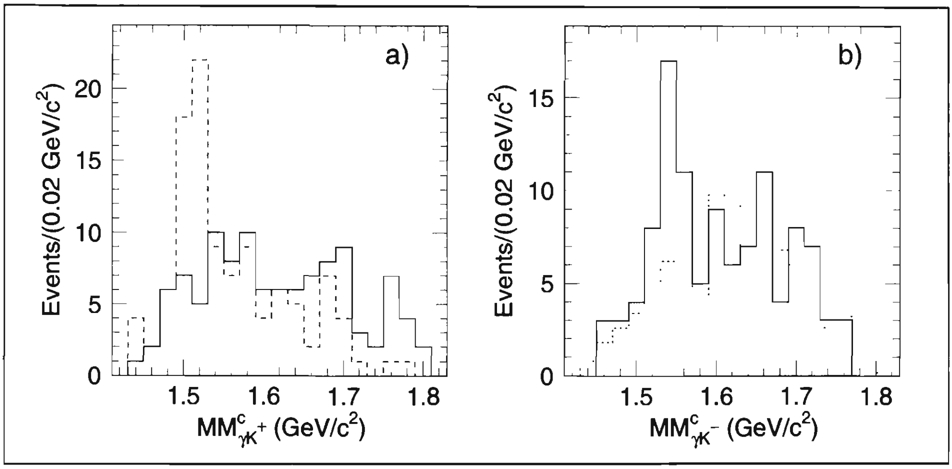

Figure 4. Data plot from LEPS for missing mass spectra of K^+ and K^- for the reactions 1 and 2, where on the x-axis are given the missing mass of the particles K^+ and K^- respectively in a) and b) respectively. On the y-axis are shown the number of events in an energy interval of 0.02 GeV/c^2. In a) and b) the solid lines correspond to the events corresponding to collisions with neutrons, while the dashed and dotted lines correspond to collisions with protons. The Λ^* resonance is seen on the left in the dotted histogram while evidence for Θ^+ is seen by the peak on the right in solid histogram.

with five quarks was identified. The complete reaction is shown in *Figure* 5. This announcement of the Θ^+ was soon followed by many other announcements. A similar experiment by the CLAS collaboration at JLAB, the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA, with deuterium instead of carbon, also observed a peak for Θ^+ pentaquark. The Θ^+ pentaquark has two main decay modes, one of which is given by (2). The other is one in which it can decay into a proton and K^0 particle. An experiment from

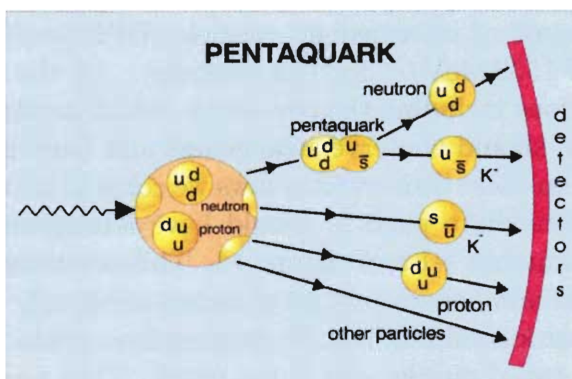

Figure 5. The pictorial representation of the reaction given by equation (2). (From http://physics.about.com/cs/physicsnews/a/010703a.htm)

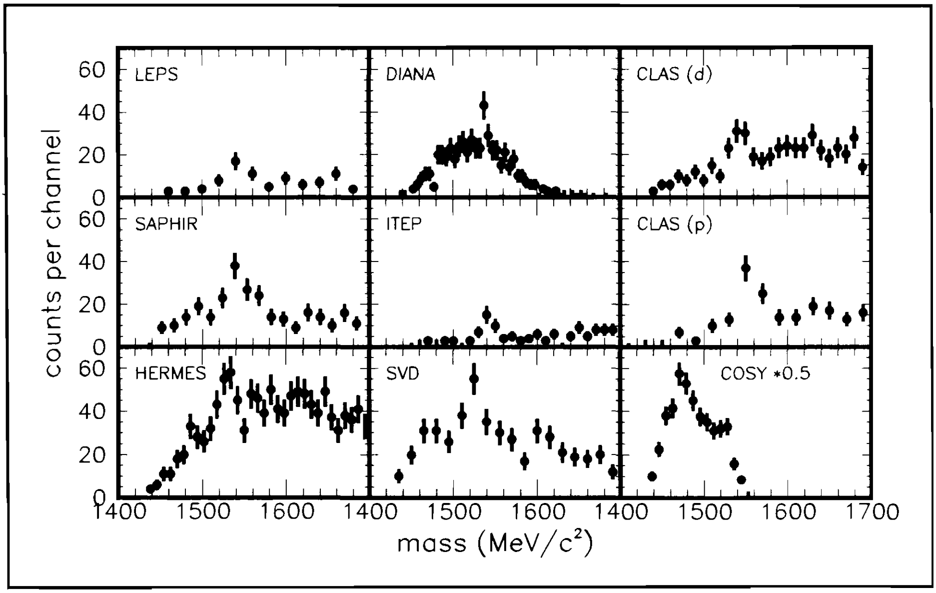

Figure 6. Data plots from different experiments showing the evidence for Θ^+ pentaquark. The reader may perceive a peak at an energy of about 1540 MeV/ c^2 in these data. The reader may see ref. [3] for a detailed discussion.

DIANA collaboration at the Institute for Theoretical and Experimental Physics (ITEP) in Dubna, Russia first reported the second kind of decay in the reaction

$$K^+ + Xe \rightarrow \Theta^+ + Xe \rightarrow K^0 + p + Xe, \qquad (3)$$

where the Xe stands for Xenon. Meanwhile, the SAPHIR collaboration at the ELSA in Bonn, HERMES and ZEUS in the DESY laboratory in Hamburg, Germany, COSY-TUF in Jülich, Germany also found evidence for the existence of Θ^+ pentaquark in different types of experiments. Their data plots are shown in *Figure* 6.

Interestingly other experiments observed peaks for other pentaquarks also. The NA49 experiment at CERN, Geneva saw evidence for a 'cascade' pentaquark Ξ^{--} with mass of 1862 MeV/c^2. It was assumed to consist of two s quarks, two d quarks and one anti-u quark. Similarly the H1 experiment at the DESY Laboratory observed a charmed pentaquark with a mass of 3099 MeV/c^2. Its composition would be two u quarks,two d quarks, one anti-c quark. (For detailed discussions on various experiments see e.g., [3].)

Is the Evidence Sufficient?

In the midst of this excitement, it is also necessary to note that some of the experiments which were expected to show the peak for pentaquarks gave nothing! The e^+e^- collision experiments did not see any evidence for pentaquarks, in that there has never been any signal for the production of say, a $\Theta^+\Theta^-$ pair, the production of which does not contradict any conservation laws provided sufficient beam energy is available in the electron and positron beams. Also the new high statistics experiment from JLAB, which claimed to see the pentaquark previously, did not see any peak. To date there are ten experiments that observed the Θ^+ pentaquark and a similar number of experiments that saw no evidence. All these experiments were done with limited statistics, so none of them could provide clinching proof. We therefore require high statistics experiments that can confirm their existence.

There are many that do not believe in the existence of pentaquarks. They attribute these peaks to 'statistical fluctuations', which can at times introduce a bump in the experimental data and to the 'cuts', removing the background due to other reactions, etc., that can introduce bias in the data. There are also other possibilities like ghost tracks (incorrectly constructed particle trails), reflection of another peak that may cause a mirage-like hump in the data. One more troublesome thing is the narrow width of Θ^+ pentaquark. The 'width' of a particle in these plots represents its inverse lifetime: the larger the width, the shorter the lifetime and vice-versa. The Θ^+ pentaquark has a lifetime larger then the predicted one. According to the theories of nuclear forces it is difficult to see why a pentaquark does not decay into a baryon and meson rapidly enough. Also these experiments claim the mass of Θ^+ pentaquark to be in the range 1525-1555 MeV/c^2 which is an extraordinarily large range. A single particle should have fixed mass.

Since all these experimental data were analyzed with care, it is hard to imagine that so many statistical fluctuations occur at the same mass (see *Figure* 6). And also these laboratories spotted the Θ^+ in different ways and reactions. Each resulted in a peak at more or less the same mass.Those experiments that did not show any peak were high energy experiments while those that showed the peak for Θ^+ were low energy experiments. Also most of the positive evidence experiments are photoproduction experiments. Perhaps there is something about them that we do not understand. Furthermore, there may be some unknown mechanism that keeps the Θ^+ from splitting into fragments and giving it a long life time. Therefore, if they exist, it will help us to learn more about the strong force that binds quarks together. Even if their existence is ruled out in future, we would need to understand why so many experiments have seen the evidence. There are proposals for new experiments at CLAS, ZEUS, COSY-TUF, KEK with high statistics which are scheduled to run later this year and in the next year. If their existence is proved then it will be necessary to study their properties like spin, parity, etc.. Since various models make different assignments for spin and parity these experiments will help in discriminating among the models. The Particle Data Group (PDG), the international body for regulating particles identification, has given 'three star' status to Θ^+ pentaquark ('three star' defined as 'Existence range from very likely to certain, but further confirmation is desirable'). There are many examples in the history of physics when experimental results are debated upon at first but are later either confirmed or shown to be wrong by more efficient experiments with higher statistics. We eagerly look forward to the experimental resolution of the question of the existence of pentaquarks.

Suggested Reading

[1] **Rohini M Godbole and Sunil Mukhi, Nobel for minus sign, *Resonance*, Vol.10, No.2, pp.33-51, 2005.**

[2] **M Oka, Theoretical overview of the pentaquark baryons, *Progress of Theor. Physics*, Vol. 112, pp.1-19, 2004. [arXiv:hep-ph/0406211].**

[3] **K Hicks, *Experimental search for pentaquarks*, arXiv:hep-ex/0504027.**

[4] **G D Coughlan and J E Dodd, *The Ideas of Particle Physics*, Cambridge University press, 1991.**

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