From decuplets to anti-decuplets and quarks to pentaquarks

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Introduction

Dozens or even hundreds of protons and neutrons can combine to form the known nuclei of atoms. But when it comes to putting quarks together to form protons, neutrons or other particles, they only come in packages of twos or threes. Or at least so it was thought until recently. For over 30 years, physicists have searched for exotic particles known as pentaquarks, that have a valence structure of four quarks and one antiquark. In the fall of 2002, evidence for a narrow baryon state having an exotic strangeness quantum number, consistent with a pentaquark structure, was presented at the PANIC conference [1]. Since then, many independent experiments have confirmed the existence of this state.

So why is this an exciting discovery? In the simplest terms, it tells us that the number of particles made from quarks is likely to be much more than just the 3-quark baryons and quark-antiquark mesons that are given in the textbooks. Furthermore, it may tell us that there are symmetries present in solutions to non-pertubative QCD that are not evident in the simple quark model. Evidence for new mesons discovered at BaBar, Belle and CLEO also suggest that the simple quark model is not adequate [2]. It may require a paradigm shift for models of hadrons.

Symmetry properties have always played a significant role in describing the spectrum of hadrons, and so it is not surprising that they have had a central role in the recent discovery of pentaquarks. In 1963, Ne'eman and Gell-Mann predicted the existence of the Ω^- consisting of three strange quarks based on the SU(3) group theory for quarks [5,6]. The discovery of the Ω^- at Brookhaven [7] three years later was a startling confirmation of the new quark model. At the heart of this model is group theory, with the lowest mass spin 1/2 baryons organized into an octet group and the spin 3/2 baryons (at higher mass) organized into a decuplet group [3]. The prediction of pentaquarks and subsequent experimental verification of their existence has renewed the interest in how quarks are bound inside hadrons.

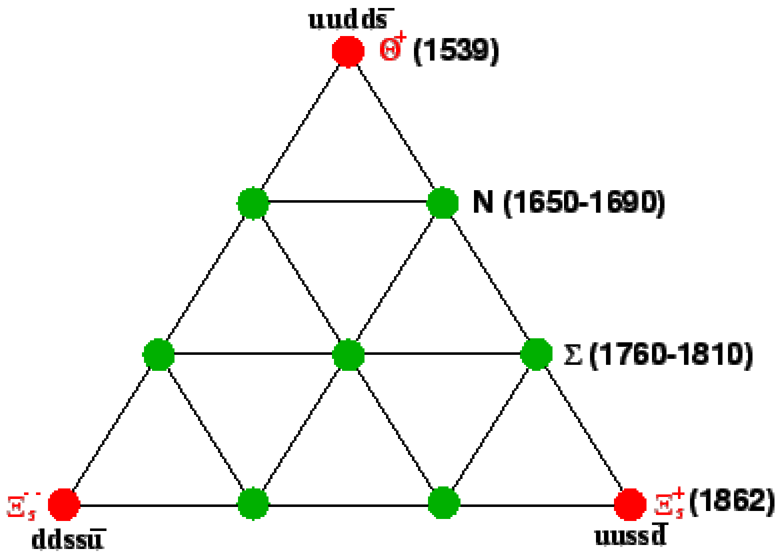

Figure 1: Pentaquarks are expected to be members of an anti-decuplet group of particles. This group is represented by plotting the strangeness of the particles vs. the third component of isospin. The three corners of the triangle (in red) are exotic, which means that their quantum numbers require more than three quarks. The masses of the states are indicated in parentheses after setting the mass of the Ω^- and Ξ_5^{--} to the observed experimental values [9].

Symmetry properties also led to the theoretical prediction of the pentaquark. While baryons are made out of three quarks (*qqq*), the pentaquark has a configuration *qqqqq*, and hence will form a different theoretical group structure. The lowest-mass pentaquark structure was known [4] to be an anti-decuplet, which is triangular like the decuplet but pointing up instead of down (see Fig.1). This anti-decuplet is predicted within the chiral soliton model as an excitation of the usual low mass octet and decuplet families. The symmetries of the model predicted, with input from some experimental masses, the mass of a pentaquark at 1.53 GeV and a decay width of only 0.015 GeV or less [9]. The quantum numbers of this particle, called the Θ^+, requires two up quarks, two down quarks and one anti-strange quark (*ududs*). The anti-strange quark cannot annihilate with the other four quarks, and hence this particle cannot be described by just three quarks.

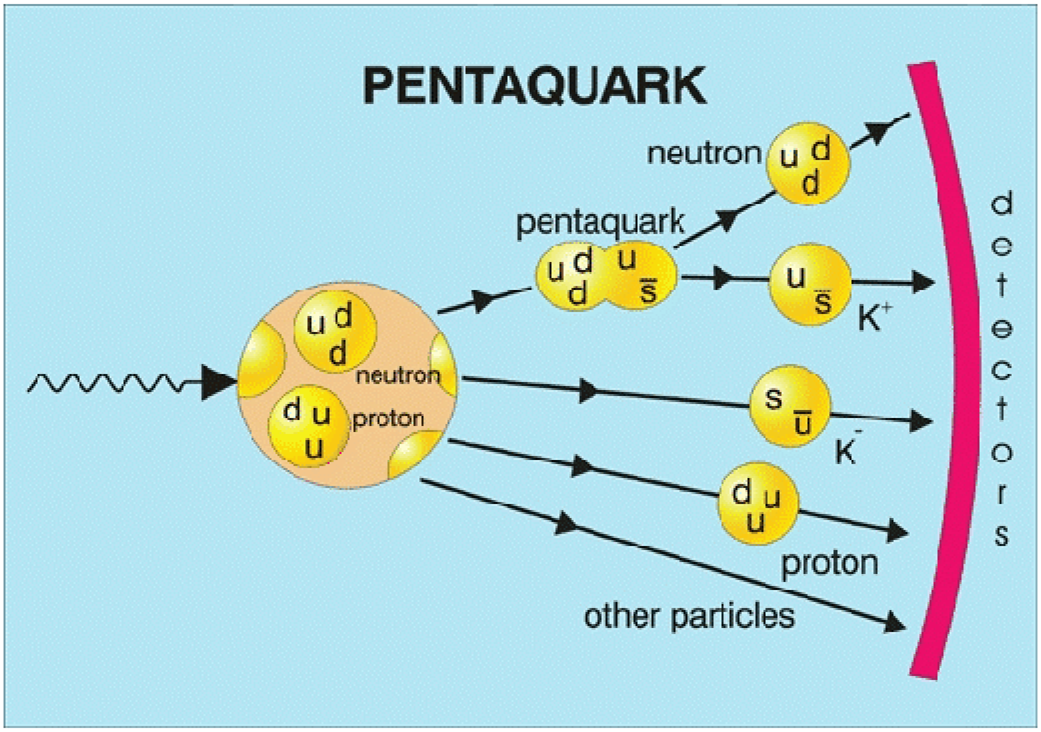

Figure 2: Detection of particles used to reconstruct the pentaquark state.

The Θ^+ can be identified experimentally by its unique strangeness quantum number. The anti-strange quark gives the Θ^+ a strangeness number of S=+1, whereas conventional three-quark baryons (like the Λ with *uds* quarks) have the opposite strangeness S=-1. Also, the Θ^+ has baryon number 1 since each quark has baryon number +1/3 and the antiquark has baryon number -1/3. The well-established principles of baryon number and strangeness conservation allow experiments to pick out the mass spectra for S=+1 final states, where no three-quark baryon can be made. A narrow peak on top of a broad non-resonant background signals the presence of a pentaquark resonance.

Experimental Evidence

The first experimental observation of the Θ^+ state came from the LEPS collaboration working at the SPring-8 facility in Japan [10]. This experiment used a high-energy photon beam incident on a carbon target producing the pentaquark state in association with a K^- particle. The Θ^+ decays almost immediately into a neutron and a K^+ as indicated schematically in Figure 2. (This state can also decay via $\Theta^+ \rightarrow pK^0$.) The pentaquark is identified as a peak in the invariant mass spectrum of its decay products as shown in the bottom panel of Figure 3. The strangeness of the Θ^+ is determined using the charge of the kaons in the reaction.

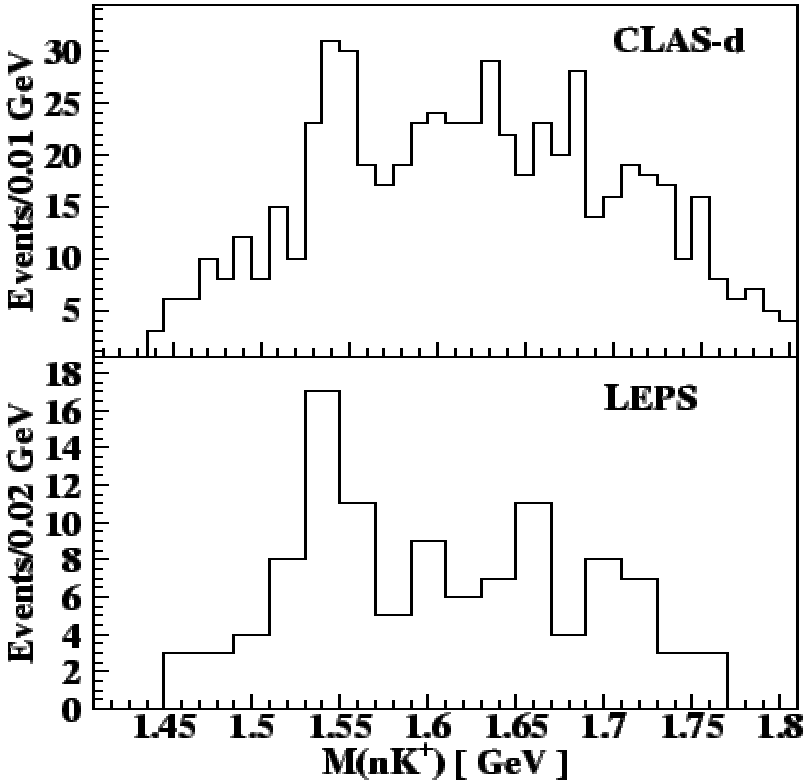

Figure 3: Invariant mass of the nK^+ system, which has strangeness S=+1, showing a peak at a mass of about 1.54 GeV/c^2. Top panel: Data from the exclusive reaction on a deuterium target from Jefferson Lab. Bottom panel: Data from the inclusive reaction on a carbon target from SPring-8.

Confirmation of this result came quickly from other laboratories around the world. To date there have been seven experimental observations of a narrow exotic S=+1 baryon state at a mass of approximately 1.54 GeV [10,11,13-17]. The measured masses of the states are shown in Figure 3. The exotic state has been observed in photon, neutrino, and proton reactions with both nuclear and proton targets. In the reactions that contain neutral kaons, these can be identified using the $K_S \rightarrow \pi^+\pi^-$ decay, but these do not uniquely determine the strangeness. Both of the θ^+ decay modes have been observed, although not in the same experiment, as indicated in Figure 2. The existence of this state is given considerable support by its observation with different probes and under very different experimental conditions.

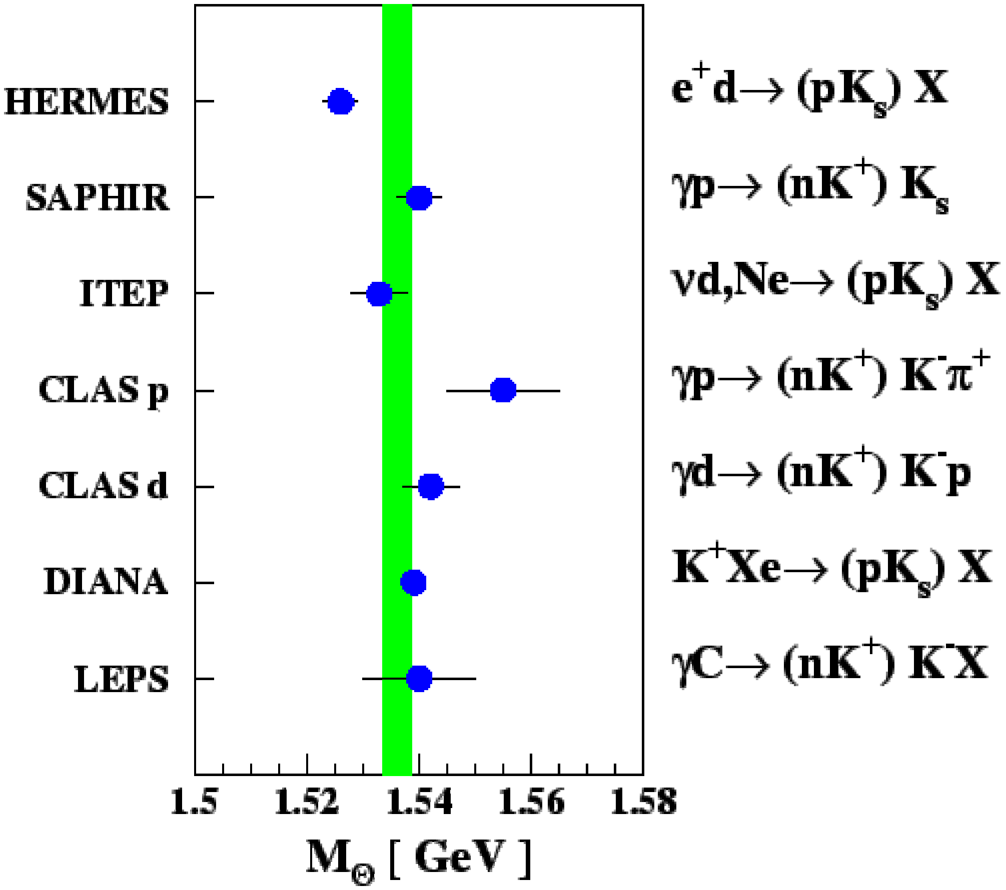

Figure 4: The mass of the Θ^+ is given for each of the experimental observations. The world average ±1 standard deviation is shown as a green band [16]. On the right we give the reaction which was used for the measurement with the Θ^+ decay mode given in parenthesis.

Photoproduction measurements of the Θ^+ on both deuteron and proton targets with the CLAS detector at Jefferson Lab [12] has provided important confirmation for this exotic baryon state and shed light on the production mechanisms which may be responsible for its production. The measurement with a deuteron target produced the Θ^+ in the reaction $\gamma d \to nK^+K^-p$, detecting all three charged particles, and reconstructed the neutron using the missing-mass technique. The complete reconstruction of the final state provided a way of reconstructing the Θ^+ using just momentum and energy conservation. The mass spectra for a S=+1 baryon final state is shown in the top panel of Figure 3 along with the data from SPring-8.

The anti-decuplet family also contains two more exotic states, denoted by Ξ_5^{--} and Ξ_5^{+}, which have S=-2 and charge Q=-2 and Q=+1, respectively. The subscript "5" indicates the five-quark (pentaquark) nature of the states. The NA49 collaboration at CERN has reported the only observation of the Ξ_5^{--} at a mass of 1.86 GeV [18]. Clearly, confirmation of this new particle is highly desired. The third exotic state, Ξ_5^{+}, not yet observed, must be found at a mass close to that of the Ξ_5^{--} in order to tie down the three corners of the anti-decuplet triangle.

Summary

In summary, evidence is mounting for the existence of an anti-decuplet family of baryons with a valence structure of 5-quarks. However, the properties of the Θ^+ S=+1 state such as spin, isospin and parity, still need to be determined before it can be conclusively identified as a member of the $J^P=½^+$ anti-decuplet, and the single observation of the Ξ_5^{--} cries out for confirmation. This new family of pentaquarks promises to rewrite our understanding of baryon spectroscopy. The implications of this discovery are being evaluated continuously in the literature [19] and we can only expect more surprises in the near future.

Acknowledgements

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[19] Updates to all work can be found in the presentations to the Penta-Quark 2003 Workshop, JLab, Nov 6-8, 2003, www.jlab.org/intralab/calendar/archive03/pentaquark/program.html.