

Hunting for pentaquarks

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According to a news release dated 16 April 2005, recent experimental data from JLAB, the Thomas Jefferson National Accelerator facility in Newport News, Virginia, USA point to the absence of the pentaquark called Θ^+ , at the place where it was expected. This surprising result due to the CLAS collaboration (where CLAS stands for the CEBAF Large Acceptance Spectrometer; CEBAF stands for the Continuous Electron Beam Accelerator Facility, which was the name of JLAB) contradicts the findings of several prior experiments, including some of its own, which indicated that at least one kind of pentaquark exists in the mass range 1525–1555 MeV/c² (for a review, see Hicks¹), while none of the experiments could definitively prove its existence. This recent experiment was based on a high energy photon beam on a liquid hydrogen target. It had considerably greater statistics; in fact, two orders of magnitude greater than a similar experiment in Germany carried out by the SAPHIR collaboration at the ELSA (Electron Stretcher Accelerator) in Bonn², which had seen evidence for the existence of pentaquarks. At JLAB, work is continuing in the hunt for pentaquarks with even higher statistics, and the data are being analysed with the possibility of publication of results later this year. The CLAS collaboration is likely to gather more data in 2006 by searching for other pentaquark candidates.

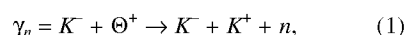
The aim of the experiments which are being discussed here, has been to establish the existence of a new state of matter. For a long time, it was believed that all observed matter at the subatomic level, that participates in the strong interactions comes in only two families. These are the ‘baryons’ and the ‘mesons’, collectively known as ‘hadrons’. For instance, protons and neutrons which are constituents of all nuclei, belong to the baryon family, while, for instance, pions which are responsible for inter-nucleon forces, belong to the meson family. Baryons are made up of three constituent quarks, while mesons are bound states of quarks and anti-quarks. Quarks themselves come in several ‘flavours’, so-called u (up) and d (down), s (strange), c (charm), t (top) and b (bottom) quarks. The neutron, for instance, is made up of two d and one u quark, while the proton is made

up of two u and one d quark. Note that the u quark has a charge of $+2e/3$, while the d quark has a charge of $-e/3$, where $-e$ is the electronic charge. Pions can be one of π^+ , π^- or π^0 . π^+ , for instance, is made up of a u quark and an anti-d quark. Of interest to us here are also ‘strange’ mesons, which could contain either a strange or an anti-s quark, called kaon. For instance, a K^+ contains a u quark and an anti-s quark. Today we have a microscopic theory of strong interactions known as quantum chromodynamics (QCD), for the interactions of ‘coloured’ quarks and gluons (the mediators of the strong force). The word ‘colour’ pertains to an internal quantum number and comes in three varieties, which have been named red, blue and green. However, this quantum number is never directly observed, and it is believed that only ‘colourless’ objects are found in the spectrum of QCD. Closely related is the hypothesis of ‘confinement’, which requires the quarks and gluons to be confined inside the hadronic matter, and the colour quantum number itself is never liberated. As a result, a quark which carries a colour and an anti-quark that contains ‘anti-colour’ can bind through the exchange of gluons which carry both colour and anti-colour to form a meson. Similarly, quarks containing each of the three primary colours can produce a colourless object. It is for the moment impossible to solve the dynamics of the theory, which has in its spectrum the baryons and mesons. Therefore, novel theoretical tools and models have to be invoked in order to gain an insight into the spectrum.

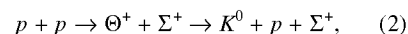
In the year 2003, several experiments reported evidence for a new state of matter in the subatomic realm which had been named ‘pentaquark’, where the particle was believed to have been composed of four quarks and one anti-quark, an arrangement compatible with the generation of a colourless object. There was tremendous excitement since mathematically such particles were the prediction of several theoretical groups working on hadron dynamics. Notable amongst these was that of Diakonov, *et al.*³, who had also predicted the mass and the lifetime of a family of pentaquarks by considering a certain effective model of the strong interaction dynamics subject to certain plausible assumptions, known as

the chiral soliton model. This model itself is too technical to be discussed in simple words, but is one in which conventional baryons are viewed as the lowest rotational states in the spectrum, while the pentaquarks appear as the next rotational state of ‘chiral solitons’, with the Θ^+ predicted to have a mass of 1530 MeV/c². For a recent review on the theory and other models of interest, see Oka⁴. Indeed, it is mathematically possible also to have configurations with two quarks and two anti-quarks (tetraquarks), three quarks and three anti-quarks (hexaquarks), etc. These would also constitute exotic hadronic matter.

The first experiment to claim evidence for the pentaquark is the SPring-8 experiment in Japan⁵. The experimental facility is at an electron synchrotron, LEPS, where electrons at an energy of 8 GeV scatter laser photons which are then used as projectiles for collision with carbon nuclei. The process is described by the reaction



where n stands for a neutron in the carbon nuclear target, and Θ^+ in the first stage of the reaction is supposed to be a pentaquark, which subsequently decays into a K^+ and n . What is observed experimentally is an enhancement in the cross-section for the production of the reaction products in the final state of eq. (1) and an energy corresponding to the mass $\times c^2$ of the Θ^+ with a measurable width. Note that the lifetime of the intermediate particle formed is the reciprocal of the width in appropriate units. It was inferred from this that the Θ^+ is a pentaquark composed of two u, two d and an anti-s quark. An experiment at CLAS in 2003 claimed to see a signal for this particle⁶ from the collisions of photons with deuterons. Furthermore, another finding from CLAS in 2004 also saw the signal from an experiment based on photon collisions with protons⁷. A more recent experiment in Jülich, Germany⁸ by COSY-TOF based on proton–proton collisions also sees evidence of Θ^+ , given by the reaction



where Σ^+ is a member of the baryon octet with one s quark.

At the earlier time, the DIANA collaboration⁹ at the Institute for theoretical and Experimental Physics (ITEP), Dubna, Russia, also reported evidence for the Θ^+ pentaquark produced in a reaction where charged kaons were collided in a bubble chamber experiment with xenon. Another experiment at the ITEP based on neutrino and anti-neutrino collisions in bubble chambers also reported evidence for the Θ^+ pentaquark¹⁰. Other notable experiments, such as the ZEUS and HERMES experiments at the HERA facility in the DESY laboratory, Hamburg, Germany, and the SVD experiment generally corroborate all the findings above, although there have been discrepancies in the determination of mass and lifetime of Θ^+ . It must also be mentioned that experiments based on e^+e^- collisions failed to see any evidence for the pentaquark.

Some experiments that could reach higher energies found evidence for other kinds of pentaquarks, notably, the NA49 experiment at CERN, Geneva, which saw a pentaquark with two s quarks, two d quarks and one u anti-quark¹¹, with a mass of 1862 MeV/c². The H1 experiment also at the HERA facility saw a pentaquark with a c anti-quark¹², with a mass of 3099 MeV/c².

In conclusion, therefore, while several experiments have claimed evidence for the existence of the pentaquark, none of them could provide clinching proof. It must also be mentioned that practically all the experiments were finding the width of Θ^+ to be significantly lower than that predicted by the chiral soliton model. (We note here that the large width predicted by

the chiral soliton model is also incompatible with present-day analysis of K^+ nucleon scattering data; see Arndt *et al.*¹³.) In fact, the most recent CLAS experiment, which is a high statistics experiment designed to detect and study Θ^+ , does not see it at all! However, there will be more experiments in the near future, which are likely to clear up the situation. It would still be necessary to understand why so many experiments were seeing evidence for Θ^+ , even if its existence is definitively ruled out by experiments that will take place in the near future. On the other hand, if the future experiments are able to establish the existence of pentaquarks, it would be necessary to study them in great detail and establish their properties, including, their parity properties for which different models make distinct predictions. Such a determination would assist in discriminating amongst the models.

1. Hicks, K., arXiv:hep-ex/0504027.
2. Barth, J. *et al.* [SAPHIR Collaboration], arXiv:hep-ex/0307083.
3. Diakonov, D., Petrov, V. and Polyakov, M. V., *Z. Phys. A*, 1997, **359**, 305 [arXiv:hep-ph/9703373].
4. Oka, M., *Prog. Theor. Phys.*, 2004, **112**, 1 [arXiv:hep-ph/0406211].
5. Nakano, T. *et al.* [LEPS Collaboration], *Phys. Rev. Lett.*, 2003, **91**, 012002 [arXiv:hep-ex/0301020].
6. Stepanyan, S. *et al.* [CLAS Collaboration], *Phys. Rev. Lett.*, 2003, **91**, 252001 [arXiv:hep-ex/0307018].
7. Kubarovsky, V. *et al.* [CLAS Collaboration], *Phys. Rev. Lett.*, 2004, **92**, 032001

[Erratum-*ibid.*, 2004, **92**, 049902 [arXiv:hep-ex/0311046].

8. Abdel-Barry, M. *et al.* [COSY-TOF Collaboration], *Phys. Lett. B*, 2004, **595**, 127 [arXiv:hep-ex/0403011].
9. Barmin, V. V. *et al.* [DIANA Collaboration], *Phys. Atom. Nucl.*, 2003, **66**, 1715. [*Yad. Fiz.*, 2003, **66**, 1763] [arXiv:hep-ex/0304040].
10. Asratyan, A. E., Dolgolenko, A. G. and Kubantsev, M. A., *Phys. Atom. Nucl.*, 2004, **67**, 682 [*Yad. Fiz.*, 2004, **67**, 704] [arXiv:hep-ex/0309042].
11. Alt, C. *et al.* [NA49 Collaboration], *Phys. Rev. Lett.*, 2004, **92**, 042003 [arXiv:hep-ex/0310014].
12. Aktas, A. *et al.* [H1 Collaboration], *Phys. Lett. B*, 2004, **588**, 17 [arXiv:hep-ex/0403017].
13. Arndt, R. A., Strakovsky, I. I. and Workman, R. L., *Phys. Rev. C*, 2003, **68**, 042201 [Erratum-*ibid.*, 2004, **69**, 019901 [arXiv:nucl-th/0308012].

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