20 YEARS OF LIGHT PENTAQUARK SEARCHES*

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Received 24 November 2024, accepted 25 November 2024, published online 16 April 2025

In this paper, I pay tribute to my exceptional colleagues and friends Dmitri Diakonov, Victor Petrov, and Maxim Polyakov by examining the experimental progress and current status of the searches of the Θ^+ pentaquark from its inception to the present.

DOI:10.5506/APhysPolB.56.3-A9

1. Introduction

As this is my contribution to the memorial volume, I would like to begin by sharing some personal reflections. My collaboration with Maxim Polyakov began in 1999 during the DIS99 Conference in Zeuthen, Germany where I was presenting experimental data from the HERMES experiment at DESY, Hamburg, Germany. It was during this time that we established a friendly relationship, and I invited Maxim to give a seminar at DESY, which he graciously accepted. From that point onward, our collaboration began.

In the year 2000, I obtained first results of the single beam-spin asymmetry in electroproduction of a single photon via interference of Deeply Virtual Compton scattering with a similar final state of the Bethe–Heitler process. It was first published as a conference proceedings [1] of the talk presented in 2000 at the Spin2000 conference in Osaka, Japan, then in 2001 published in *Physical Review Letters* [2]. Now it is dubbed as DVCS and is well known to the community of DESY, CERN, and JLab, and constitutes one of the major parts of the physics program of the newly proposed Electron Ion Collider under construction at Brookhaven National Laboratory, USA. Later, Maxim made significant contributions to observe the D-term for the General Parton Distributions and measurement of the pressure inside the proton. All this is well known and I would not like to further bother the reader with the details of these avenues.

In 2002, an international workshop was held in Santorini, Greece. Along with Maxim, Mitya Diakonov and Vitya Petrov participated in it. This is where I met them for the first time and later we collaborated closely. In this meeting, there was no word mentioned to me about their seminal work on pentaquarks [3].

In 2003, I was invited to the DIS2003 in Sankt Petersburg, Russia, where for the first time I heard about the Θ^+ exotic baryon made of $uudd\bar{s}$ quarks. I promised Diakonov, Petrov, and Polyakov to look at the $pK_{\rm S}$ decay channel of Θ^+. And apparently, we observed a peak in the invariant mass of $pK_{\rm S}$ from the HERMES data and after a long review and discussions, it was finally published [4]. The results obtained by the HERMES Collaboration initiated also other HERA experiments to look for Θ^+. The ZEUS Collaboration reported the observation of Θ^+ in their data [5], while H1 and HERAB did not. These outcomes created heated debates in the DESY community, there was an extraordinary seminar organized, with all four experiments at HERA, where I gave an opening experimental talk and Maxim gave a theory presentation. Things were not conclusive as none of the HERA experiments was really designed for hadron spectroscopy.

In 2003, the SPring-8 published their first observation of Θ^+ in photoproduction on a carbon target [6], and independently, in the same year, there was a paper by the DIANA experiment on a bubble chamber with observation of Θ^+ in the $K + n \to K^0 p$ reaction on the Xe target [7]. Consequently, in the same year, the CLAS Collaboration at Jefferson Laboratory (JLab) claimed observation of Θ^+ in photoproduction experiments on a deuteron as well as on hydrogen targets.

In the two following years, there were hundreds of papers published by theorists on the topic of exotic baryons. I may have not listed all experiments, for the detailed review, I refer to [9] and [10]. All this created high excitement in the community until the CLAS Collaboration remeasured their previous channels with high statistics and did not confirm their reported claims of observation of Θ^+. This was announced on the first day of the APS meeting in Tampa, FL, in 2005 where I was invited to give a talk on pentaquarks two days later.

One can imagine the level of skepticism created by the CLAS announcement. Anyway, I want just to remind the reader that, as Carl Sagan once said: "Absence of evidence is not evidence of absence". I said something similar in my talk, however, as the English proverb says: "too many cooks spoil the broth".

Coming back to Norfolk, where I was already hired as a professor of physics at Old Dominion University and doing research in CLAS at JLab, I decided to look at the Quantum Mechanical interference between ϕ and Θ^+ produced with the same final state, *i.e.* $\gamma + p \to p\phi \to pK_{\rm S}K_{\rm L}$, which in more detail is described in Section 2.

In the meantime, I was thinking about how to create the two-body reaction to answer the question of existence or non-existence of Θ^+ and came to the idea of creating a secondary beam of neutral kaons and submitted a letter of intent to the JLab Program Advisory Committee (PAC) in 2015, which is discussed in Section 3. Unfortunately, all my theory colleagues, Dmitri Diakonov, Victor Petrov, and Maxim Polyakov by now passed away and will not see the future results.

2. Theory and experiment

In his paper, classifying all existing baryons into octet and decuplet of SU(3) symmetry, Gell-Mann predicted the existence of multiquark states different from the regular 3-quark states for baryons, *i.e.* 5-quarks in particular [8]. However, multiple attempts over the decades did not prove the existence of such configurations. The breakthrough happened after the publication of Diakonov, Petrov, and Polyakov [3], in which authors predicted the existence of the particle in the apex of anti-decuplet, the so-called Z-baryon, later dubbed as Θ^+ with a mass of 1530 MeV and a relative narrow width of the order of 15 MeV decaying either to K^+n or K^0p. Other members of anti-decuplet were also predicted with exotics on the corners of the diagram, see Fig. 1.

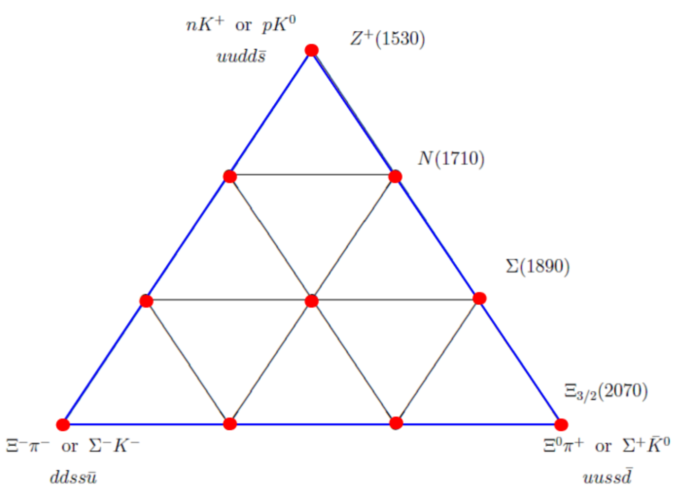

Fig. 1. The suggested anti-decuplet of baryons [3]. The corners of this (T_3, Y) diagram are exotic. The original name of the pentaquark lying at the apex of $\overline{10}$ was Z^+, then following Diakonov's suggestion, it was called Θ^+.

There was a period of a long silence until the SPring-8 [6] and Diana experiments [7] announced the observation of Θ^+. Then many experimental facilities tried to observe it, see review papers [9] and [10].

Without going into details of the Quark Soliton Model, I should mention that hundreds of papers were published in a short period of time until the 2005 APS meeting in Tampa, Florida. I was invited there to give a talk on pentaquarks, but on the first day of that meeting the CLAS Collaboration announced non-observation of Θ^+ in a new set of high statistics experiments and obviously my talk looked like a "shot in the air". Thus since then, the situation has changed and the community has come to the conclusion that pentaquarks do not exist at all and we should forget about them.

Just then I started thinking about how to try to observe Θ^+ after all, if it exists. For that, Maxim, Mitya, and I started to analyze theoretically the interference between two reactions $\gamma + p \to p\phi \to pK_{\mathrm{S}}K_{\mathrm{L}}$ and $\gamma + p \to K_{\mathrm{S}}\Theta^+ \to pK_{\mathrm{S}}K_{\mathrm{L}}$ [11]. According to Quantum Mechanics, these two processes should interfere as the initial and final states of the two above reactions are the same.

We performed an analysis of the CLAS data looking at the pK_{L} distribution for the events selected under the ϕ peak, which was extremely clean. As a result, we observed a peak in the invariant mass of pK_{L} which could not be explained based on the ϕ production alone with extensive Monte Carlo simulations. The CLAS Collaboration appointed a few review committees and we even created a web page where every member of the CLAS Collaboration could ask questions. We produced hundreds of plots and answered all kinds of questions, however, the CLAS Collaboration was still reluctant to approve our analysis for the publication.

The problem of the three-body final state is well known, there are many overlapping resonances in the combinatorial combinations and they may bury existent particle. The interference is one way to avoid such an overlap. After many years of debates, in 2012, a small group of enthusiasts decided to publish these results and we posted the manuscript on `arXiv` and submitted the paper to *Physical Review C*, where in a short time it was published [12]. This was a very long story. In Fig. 2 we show that for events under the ϕ peak from the fit we observe a resonance in the missing mass of K_{S} with the following parameters: the peak in the missing mass $M_X(K_{\mathrm{S}}) = 1.543 \pm 0.002$ GeV with a Gaussian width $\sigma = 0.006$ GeV and statistical significance of 5.3σ.

Subsequently, the CLAS Collaboration published a comment paper [13], arguing that authors of [12] used a cut on the t-Mandelstam variable, which influenced the Θ^+ peak. The fact that the mechanism of the ϕ or Θ^+ production can change depending on the range of the t-Mandelstam was not accepted and was criticized by the authors of Ref. [13], although the subsequent paper on the ϕ production, where we showed that at least the mechanism of the ϕ production changes depending on a t-range [14], was signed by the entire CLAS Collaboration and nobody paid attention that it essentially dismissed the counterargument in the comment paper [13].

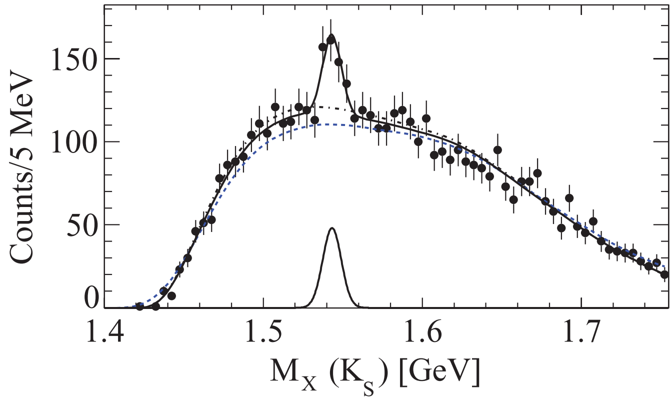

Fig. 2. Missing mass of K_{S} with a cut $-t_{\Theta} < 0.45$ GeV^2. The dashed line is the result of a ϕ Monte Carlo simulation, the dash-dotted line is a modified Monte Carlo distribution, and the solid line is the result of a fit with a modified Monte Carlo distribution plus a Gaussian function.

3. Aftermaths

After all these twists and turns, a question remains how to perform a two-body experiment with Θ^+ produced in a formation reaction. For that purpose, one needs to search for Θ^+ in the $K^0 + p \to K^+ n$ reaction. How to make a beam of neutral kaons with a high intensity to make this possible? As mentioned in Introduction, a letter of intent was submitted to the JLab Program Advisory Committee (PAC) in 2015. After a few years, the proposal endorsed by 160 physicists from 19 countries was finally approved in 2020 by the PAC48 for the secondary beam of K_{L} to run in Hall D of JLab for 200 days of a beam time [15]. Since it overlaps with already approved programs in Hall D, the experiment may be scheduled to start in 2028. We are now working on a realization of this K-long Facility (KLF) project.

A long story, but this is what it is. I should mention that as the pentaquark *per se* is a very sensitive topic, the proposal was written for the hadron spectroscopy without mentioning Θ^+. However, in 2024, we turned our attention to the $K_{\mathrm{L}} + p \to K^+ n$ reaction and we published the paper [16], where it is shown that if Θ^+ does exist, then thousands of them will be observed in 100 days of running. As one can see from Fig. 3 we should observe many thousands of Θ^+ with a very narrow 1–2 MeV experimental width. Otherwise, if it is not observed, then one should forget it and bury Θ^+ under the stone forever, as the sensitivity of this reaction exceeds the level of any reasonable doubt.

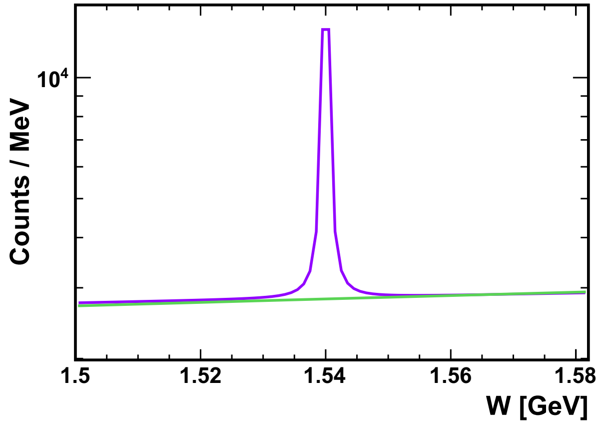

Fig. 3. Expected number of events in $K_{\mathrm{L}}p \to K^+n$ reaction as a function of W for 100 days of running on the hydrogen target at the GlueX setup in Hall D at JLab (for details, see Ref. [16]).

I am indebted to editors of the *Acta Physica Polonica B* for providing me the opportunity to contribute to the memorial volume dedicated to my great colleagues Dmitry Diakonov, Victor Petrov, and Maxim Polyakov. This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award No. DE FG02-96ER40960.

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