PENTAQUARKS AND MAXIM V. POLYAKOV*

Hyun-Chul Kim

Hadron Theory Group and Department of Physics, Inha University
100 Inha-Ro, Incheon 22212, Korea
hchkim@inha.ac.kr

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This brief review is dedicated to the memory of Maxim V. Polyakov and his pioneering contributions to pentaquark physics. We focus on his seminal 1997 work with Diakonov and Petrov that predicted the Θ^+ pentaquark, a breakthrough that initiated an intense period of research in hadron physics. The field faced a significant setback when the CLAS Collaboration at Jefferson Lab reported null results in 2006, leading to a dramatic decline in light-pentaquark research. Nevertheless, Maxim maintained his scientific conviction, supported by continued positive signals from the DIANA and LEPS collaborations. Through recent experimental findings on the Θ^+ and the nucleon-like resonance $N^*(1685)$, we examine how Polyakov's theoretical insights, particularly the prediction of a narrow width ($\Gamma \approx 0.5$–1.0 MeV), remain relevant to our understanding of the Θ^+ light pentaquark.

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1. Remembering Maxim

I first met Maxim Vladimirovich Polyakov in October 1993 at the Institute for Theoretical Physics II at Ruhr-University Bochum. He and Pasha Pobylitsa came as guest scientists, both fresh-baked Ph.D.s like myself. After a couple of discussions, I was surprised by their maturity in theoretical physics. They were not fresh-baked theoretical physicists but full-fledged ones. This was no surprise, as their advisor Mitya Diakonov once told me that he accepted only students in his group, who could challenge him intellectually. Rather than feeling discouraged by their expertise, I decided to learn from them. Our discussions were characterized by direct, unvarnished feedback — "*Hyun-Chul, you're absolutely wrong!*" was a common refrain. Maxim told me that such a discussion must be natural in physics, and was a long tradition in the Landau and Gribov school.

I worked with Maxim on various subjects. Of all the research I conducted with him, the study on nucleon tensor charges stands out as the most memorable [1]. I received an email from Maxim in the Autumn of 1995, while he was visiting the University of Bern. In the email, he wrote: "*My goodness, Hyun-Chul. I totally forgot the tensor charges of the nucleon! We can compute them in our model. Since you have already calculated the axial-vector form factors of the nucleon, you can immediately derive the tensor charges of the nucleon. In this case, anomalous contributions come from the real part of the effective chiral action.*" After I replied, I began computing the nucleon tensor charges, which took about ten days. Once he returned to Bochum, we discussed the results and physical implications of the nucleon tensor charges. We wrote a manuscript together. It was truly an amusing experience.

When I got a permanent position in Korea, I regularly visited Bochum. One of the main reasons for my visits was to discuss physics with Maxim. In doing theoretical physics, one of the most important things is to find the right person for discussion. Maxim was such a person. When I had an idea, I always wanted to discuss it with him to see if it was viable. He also visited Korea several times and even attended my student's wedding ceremony. He enjoyed visiting Korea because the atmosphere reminded him of the Siberian mentality and hospitality.

Fig. 1. Maxim V. Polyakov and Hyun-Chul Kim at the 10^{th} International Conference on Structure of Baryons (Baryons 2004) in Paris, 2004.

That is how we became colleagues, then friends, and finally brothers when he gave me a small silver cross, saying, "*In Russia, giving a silver cross to somebody means that you are my brother.*" His contributions to physics were profound: the prediction of the light pentaquark with Diakonov and Petrov [2], pioneering work on hard exclusive electroproduction of two pions [3], significant advances in generalized parton distributions [5], and fundamental insights into the mechanical structure of the proton [6]. His 2002 work on proton mechanical structure and gravitational form factors [7, 8] remains particularly relevant for the upcoming electron–ion collider (EIC) experiments aimed at understanding proton mass and spin [9–11].

Maxim's sudden passing left an irreplaceable void, both personally and in our field. His ability to bridge sophisticated theory with experimental observables was rare and valuable. Beyond his scientific achievements, I lost a brother who shared not only physics discussions but also life's broader journey. His contributions continue to guide our understanding of hadronic physics, especially as we approach the era of new experimental facilities.

2. A very brief history on pentaquarks

In the present review, I will focus on the pentaquark states among many important Maxim's works. This can be a complementary one to recent reviews by Amaryan [12], Praszałowicz [13], and Strakovsky [14]. The paper with the title «Exotic anti-decuplet of baryons: prediction from chiral solitons» [2] predicted the mass and width of an $S = +1$ baryon to be $M_{\Theta^+} \approx 1530$ MeV and $\Gamma_{\Theta^+} \approx 15$ MeV, which is a member of the baryon antidecuplet ($\overline{10}$). The quark content of the $S = +1$ baryon is known to be $uudd\bar{s}$, that is, a pentaquark state. This new baryon was at first called Z^+, and later christened Θ^+ by Diakonov [14]. The existence of the pentaquark Θ^+ was for the first time experimentally confirmed by the LEPS Collaboration at SPring-8 [15]. Then many experimental groups [16–23] consecutively confirmed its existence. The findings were phenomenal and triggered numerous works on the light pentaquark Θ^+.

Pentaquark states were first investigated in K^+N and K^+d experiments in the 1960s [24–27] as well as in photoproduction experiments [28]. The experimental signals observed in these studies were all broad and were hypothesized to be pentaquark states belonging to either the baryon antidecuplet or the baryon eikosiheptaplet (**27**). Golowich analyzed the data on K^+N scattering, and proposed the existence of $Z_0^*(1700)$ and $N^*(1750)$ [29]. However, all these proposed pentaquark states had broad widths. The mass of the Θ^+ was also predicted in Skyrme models [30, 31]. Notably, while Biedenharn *et al.* [30] mentioned that they eliminated an unwanted antidecuplet ($M_{\overline{\mathbf{10}}} \approx 1500$ MeV), Praszałowicz predicted the mass of the pentaquark with strangeness $S = +1$ as $M_{\overline{\mathbf{10}}} \approx 1530$ MeV, stating that whether this prediction was a success or a drawback of the model would depend on the reader's perspective [31]. Therefore, the significance of Ref. [2] lies not only in its mass prediction but also in its prediction of the small width of the Θ^+.

High-energy experiments reported negative results for the existence of the Θ^+ [32–38]. In 2006, the CLAS Collaboration reported null results regarding the existence of the Θ^+ [39–41]. The E522 experiment at KEK also searched for the Θ^+ using the inclusive $\pi^- p \to K^+ X$ and $K^+ p \to \pi^+ X$ reactions, but did not find any significant signal [42, 43]. Following these results, publications on pentaquarks decreased dramatically, and the scientific attitude toward light pentaquarks became increasingly skeptical until the discovery of heavy pentaquark states $P_{c\bar{c}}$ [44–46]. Nevertheless, the LEPS and DIANA collaborations continued to report evidence for the existence of the Θ^+ [47–51]. For detailed discussions of both positive and negative experimental results, see a recent paper by Amaryan [12].

Several important questions regarding the pentaquark Θ^+ remain unanswered. Following the initial discovery by the LEPS Collaboration, multiple experiments confirmed the existence of the Θ^+. If the Θ^+ indeed does not exist, what were the peaks that multiple experimental groups identified as the Θ^+? Most experiments that yielded positive results for the existence of the Θ^+ used real and virtual photons scattered off the nucleon, deuteron, or nuclei. However, it is noteworthy that the null results from the CLAS Collaboration also came from photoproduction experiments. In contrast, the experiments that did not observe the Θ^+ were primarily based on e^+e^- annihilation to hadrons. The reason for this experimental discrepancy remains unclear.

With the exception of the DIANA Collaboration [16], no experiments used kaon beams. The Θ^+, if it exists, would primarily decay into K^+n or K^0p. This suggests that a kaon beam with appropriate momentum could be used to form the Θ^+ directly [52, 53]. Notably, the DIANA Collaboration has continued to report evidence for the existence of the Θ^+ [49–51]. DIANA utilized a liquid xenon bubble chamber through which the K^+ beam passed. Using this setup in the $K^+\mathrm{Xe} \to K^0 p \mathrm{Xe}'$ reaction, DIANA reported the mass and width of Θ^+ as $M_{\Theta^+} = (1538 \pm 2)$ MeV and $\Gamma_{\Theta^+} = (0.34 \pm 0.10)$ MeV, respectively. Additionally, a break-away group from the CLAS Collaboration reported the observation of the Θ^+ in $^1\mathrm{H}(\gamma, K^0_\mathrm{S})X$ through interference with ϕ-meson production [54].

The use of kaon beams provides a significant advantage in searching for $S = +1$ pentaquark baryons, as the Θ^+ can be formed through direct formation. Several experimental proposals to search for the Θ^+ have been put forward. Following the suggestion by Sekihara *et al.* [53], Ahn and Kim [55] proposed searching for the Θ^+ using the $K^+d \to K^0pp$ reaction. The KLF Collaboration proposed investigating elastic $K_\mathrm{L}p \to K_\mathrm{S}p$ and charge-exchange $K_\mathrm{L}p \to K^+n$ reactions [56, 57]. These new proposals may definitively resolve the question of the Θ^+'s existence in the near future.

In the work of Diakonov, Petrov, and Polyakov [2], the critical assumption was that the P_{11} resonance $N^*(1710)$ was a nonstrange member of the baryon antidecuplet. Polyakov and Rathke examined the radiative decays of this nonstrange member and discovered that the transition magnetic moment for the neutron channel is much larger than that for the proton, a phenomenon they termed the *neutron anomaly* [58]. Based on this finding, they proposed that this nonstrange member could be identified in *antidecuplet friendly photoproductions* such as $\gamma n \to K^+\Sigma^-$, $\gamma n \to \eta n$, and $\gamma n \to (\pi\pi)_{I=1}N$. The key insight here is that a neutron target is more favorable for producing neutron-like pentaquarks.

Kuznetsov *et al.* [59, 60] first reported on the existence of a nucleon-like narrow resonance at around 1.68 GeV, which was subsequently confirmed by the CBELSA/TAPS Collaboration [61–63], A2 Collaboration [64], and at the Laboratory of Nuclear Science (LNS), Tohoku University [66]. This narrow resonance could naturally be identified as a neutron-like pentaquark belonging to the baryon antidecuplet within the χQSM [58, 67]. With this new pentaquark resonance, the experimental data on $\gamma n \to \eta n$ were well described within reaction models [68–70]. Furthermore, this narrow $N^*(1685)$ resonance played an essential role in describing the $\gamma n \to K^0\Lambda$ reaction near the threshold [71]. However, alternative interpretations were proposed, including coupled-channel effects of known nucleon resonances [72, 73], contributions from intermediate strangeness states [74], and interference in the partial wave between contributions from the well-known $N^*(1535)$ and $N^*(1650)$ resonances [75]. While additional experimental evidence is needed to definitively identify the nature of the narrow resonance $N^*(1685)$, Maxim argued for the simplest interpretation of $N^*(1685)$ as a neutron-like pentaquark, citing the *principle of economy* or *Occam's razor* [76].

3. Masses of Θ^+ and $N^*(1685)$

In this section, we will briefly review an extended analysis from Ref. [2], based on Refs. [77, 78]. Witten demonstrated that in the large-N_c limit of quantum chromodynamics (QCD), where N_c is the number of colors, a baryon emerges as a bound state of N_c valence quarks in a pion mean field [79]. The N_c valence quarks generate an effective pion mean field that arises from vacuum polarization, and the same valence quarks are then bound by this self-consistently generated field. This classical mean-field solution can also be described as a chiral soliton with hedgehog symmetry, which represents the minimal generalization of spherical symmetry [80, 81]. The chiral quark–soliton model (χQSM) [82–84] is founded on Witten's seminal idea. Since meson fluctuations are suppressed in the large-N_c limit, the path integral over the pseudo-Nambu–Goldstone boson (pNGB) fields can be evaluated using a saddle-point approximation. The chiral soliton emerges as a solution by minimizing the classical nucleon mass self-consistently, taking into account both the energies of the N_c valence quarks (level quarks) and the sea quarks (Dirac continuum). A key strength of this pion mean-field approach is its ability to describe both low-lying light baryons and singly heavy baryons within a unified framework [85].

Since the classical nucleon represented by the chiral soliton lacks quantum numbers such as spin and isospin, quantization is necessary. While meson fluctuations are suppressed by the $1/N_c$ expansion, a complete consideration of zero modes, which arise from rotational and translational symmetries, remains essential. This zero-mode quantization in flavor SU(3) leads to the effective collective Hamiltonian [2, 77, 86]

$$H = M_{\mathrm{cl}} + H_{\mathrm{rot}} + H_{\mathrm{sb}}\,, \tag{1}$$

where M_{cl} corresponds to the classical mass of the chiral soliton. H_{rot} represents the $1/N_c$ rotational Hamiltonian given by

$$H_{\mathrm{rot}} = \frac{1}{2I_1}\sum_{i=1}^{3}\hat{J}_i^2 + \frac{1}{2I_2}\sum_{p=4}^{7}\hat{J}_p^2\,, \tag{2}$$

where J_i and J_p are generators of the flavor SU(3) group, with J_i representing the usual spin operators. $I_{1,2}$ indicate the SU(3) soliton moments of inertia, determined through the specific dynamics of chiral solitonic approaches such as the χQSM or the Skyrme model. H_{sb} represents the explicit SU(3) symmetry-breaking term [77], which takes the form

$$\begin{aligned} H_{\mathrm{sb}} \;=\; & (m_d - m_u)\left(\frac{\sqrt{3}}{2}\,\alpha\, D^{(8)}_{38}(\mathcal{R}) + \beta\,\hat{T}_3 + \frac{1}{2}\,\gamma\sum_{i=1}^{3} D^{(8)}_{3i}(\mathcal{R})\,\hat{J}_i\right) \\ & + (m_s - \bar{m})\left(\alpha D^{(8)}_{88}(\mathcal{R}) + \beta\,\hat{Y} + \frac{1}{\sqrt{3}}\,\gamma\sum_{i=1}^{3} D^{(8)}_{8i}(\mathcal{R})\,\hat{J}_i\right) \\ & + (m_u + m_d + m_s)\,\sigma\,, \end{aligned} \tag{3}$$

where m_u, m_d, and m_s denote the current quark masses for up, down, and strange quarks, respectively. Here, $\bar{m}$ indicates the average of up and down quark masses. The $D^{(\mathcal{R})}_{ab}(\mathcal{R})$ desginate the SU(3) Wigner D functions, while $\hat{Y}$ and $\hat{T}_3$ act as operators for the hypercharge and isospin third component, respectively. The parameters α, β, and γ can be written in terms of the πN sigma term, $\varSigma_{\pi N}$, and soliton moments of inertia $I_{1,2}$ and $K_{1,2}$ as

$$\alpha = -\left(\frac{2}{3}\frac{\varSigma_{\pi N}}{m_u + m_d} - \frac{K_2}{I_2}\right)\,, \qquad \beta = -\frac{K_2}{I_2}\,, \qquad \gamma = 2\left(\frac{K_1}{I_1} - \frac{K_2}{I_2}\right)\,. \tag{4}$$

The σ is proportional to $\Sigma_{\pi N}$

$$\sigma = -(\alpha+\beta) = \frac{2}{3}\frac{\Sigma_{\pi N}}{m_u + m_d}\,. \tag{5}$$

The eighth of the generators of the SU(3) group is constrained by the collective quantization

$$J_8 = -\frac{N_c}{2\sqrt{3}}B = -\frac{\sqrt{3}}{2}\,, \qquad Y' = \frac{2}{\sqrt{3}}J_8 = -\frac{N_c}{3} = -1\,, \tag{6}$$

where B denotes the baryon number. In the χQSM, this baryon number emerges from the N_c valence quarks occupying the discrete level [83, 86], whereas in the SU(3) Skyrme model, it originates from the Wess–Zumino term [87–89]. This constraint limits the allowed representations to SU(3) irreducible representations with zero triality. Consequently, the permissible $\mathrm{SU(3)}_f$ multiplets include the baryon octet ($J = 1/2$), decuplet ($J = 3/2$), and antidecuplet ($J = 1/2$), among others. This feature underscores the success of collective quantization and highlights a distinctive duality between a rigidly rotating soliton and a constituent quark model.

The baryon collective wave functions can be formulated using the SU(3) Wigner D functions in representation $\mathcal{R} = \mathbf{8},\, \mathbf{10},\, \overline{\mathbf{10}}, \cdots$

$$\begin{aligned}&\langle A|\mathcal{R},\, B(Y\,T\,T_3,\; Y'\,J\,J_3)\rangle\\ &= \Psi^{(\mathcal{R}\,;\,Y\,T\,T_3)}_{(\mathcal{R}^*\,;\,Y'\,J\,J_3)}(A) = \sqrt{\dim(\mathcal{R})}\,(-)^{J_3+Y'/2}\,D^{(\mathcal{R})*}_{(Y,T,T_3)(-Y',J,-J_3)}(A)\,,\end{aligned} \tag{7}$$

where Y, T, T_3 correspond to the hypercharge, isospin, and its third component for a given baryon, respectively. The symmetry-breaking term in the collective Hamiltonian (Eq. (3)) induces mixing between different $\mathrm{SU(3)}_f$ representations. Consequently, the collective wave functions incorporate corrections from other allowed representations due to SU(3) symmetry breaking

$$\begin{aligned}|B_8\rangle &= |8_{1/2}, B\rangle + c^B_{\overline{10}}\,|\overline{10}_{1/2}, B\rangle + c^B_{27}\,|27_{1/2}, B\rangle\,,\\ |B_{10}\rangle &= |10_{3/2}, B\rangle + a^B_{27}\,|27_{3/2}, B\rangle + a^B_{35}\,|35_{3/2}, B\rangle\,,\\ |B_{\overline{10}}\rangle &= |\overline{10}_{1/2}, B\rangle + d^B_{8}\,|8_{1/2}, B\rangle + d^B_{27}\,|27_{1/2}, B\rangle + d^B_{\overline{35}}\,|\overline{35}_{1/2}, B\rangle\,.\end{aligned} \tag{8}$$

The detailed expressions for the coefficients in Eq. (8) are available in Ref. [77].

Beyond the explicit SU(3) symmetry breaking, we have incorporated isospin symmetry-breaking effects arising from the up and down current quark mass difference, manifested in the first term of H_{sb} in Eq. (3). Furthermore, our analysis includes isospin symmetry breaking from electromagnetic self-interactions [90]. This comprehensive treatment of symmetry breaking enables a more refined analysis compared to previous studies [2, 92].

The zero-mode collective quantization with hedgehog symmetry functions independently of any specific chiral solitonic approach. This universality implies that under hedgehog symmetry and explicit flavor SU(3) symmetry breaking, Eqs. (1) and (2) take a model-independent form. Consequently, rather than calculating parameters within specific chiral-soliton models, we can determine the moments of inertia and other parameters (α, β, γ, *etc.*) using experimental and empirical data. To compute the baryon decuplet and antidecuplet masses, we utilize the experimental baryon octet masses. Additionally, determining the moments of inertia I_1 and I_2 requires at least two mass inputs from the baryon antidecuplet. For this purpose, we adopt the masses of Ω and Θ: $M_\Omega = (1672.45 \pm 0.29)$ MeV [91] and $M_{\Theta^+} = (1524 \pm 5)$ MeV [47]. The inclusion of isospin symmetry breaking allows for the unambiguous determination of all parameters.

To validate our theoretical framework, we initially calculated the masses of the baryon decuplet (**10**). As shown in Table 1, the pion mean-field approach yields results in excellent agreement with the PDG data [91], with the exception of the Δ isobar masses. The discrepancy in Δ baryon masses, ranging from 10 to 20 MeV, remains acceptable given their substantial decay widths ($\Gamma_\Delta \approx (114–120)$ MeV). Having confirmed the reliability of the theoretical framework, we can proceed with evaluating the baryon antidecuplet masses. Table 2 presents our calculated masses for the baryon antidecuplet alongside results from previous studies [2, 93]. While Ledwig *et al.* [93] derived the dynamical parameters within the SU(3) χQSM framework under isospin symmetry constraints, the current approach yields $N^*(1685)$ masses

Table 1. Predicted masses of the baryon decuplet. The experimental data of decuplet baryons are taken from the Particle Data Group (PDG) [91].

Mass [MeV]		T_3	Y	Experiment [91]	Predictions
M_Δ	Δ^{++}	$3/2$	1	1231–1233	1248.54 ± 3.39
	Δ^{+}	$1/2$			1249.36 ± 3.37
	Δ^{0}	$-1/2$			1251.53 ± 3.38
	Δ^{-}	$-3/2$			1255.08 ± 3.37
M_{Σ^*}	Σ^{*+}	1	0	1382.83 ± 0.34	1388.48 ± 0.34
	Σ^{*0}	0		1383.7 ± 1.0	1390.66 ± 0.37
	Σ^{*-}	-1		1387.2 ± 0.5	1394.20 ± 0.34
$M_{\Xi^{*0}}$	Ξ^{*0}	$1/2$	-1	1531.80 ± 0.32	1529.78 ± 3.38
	Ξ^{*-}	$-1/2$		1535.0 ± 0.6	1533.33 ± 3.37
$M^\star_{\Omega^-}$	Ω^-	0	-2	1672.45 ± 0.29	Input

that are in good agreement with experimental observations [94]. Although the predicted $\Xi_{3/2}$ masses exceed those reported by the NA49 Collaboration [95], it should be noted that these experimental values currently lack independent confirmation from other experiments.

Table 2. Comparison of the results for the masses of the baryon antidecuplet. It is important to emphasize that the data from the NA49 experiment [95] still requires independent experimental verification.

Mass		Diakonov *et al.* [2]	χQSM [93]	Exp.	Ref. [77]
M_{Θ^+}	Θ^+	1530	1538	1524 ± 5 [47]	Input
M_{N^*}	p^*	$1710^\star$	1653	1686 ± 12 [94]	1688.18 ± 10.53
	n^*				1692.16 ± 10.53
$M_{\Sigma_{\overline{10}}}$	$\Sigma^+_{\overline{10}}$	1890	1768		1852.35 ± 10.00
	$\Sigma^0_{\overline{10}}$				1856.33 ± 10.00
	$\Sigma^-_{\overline{10}}$				1858.95 ± 10.00
$M_{\Xi_{3/2}}$	$\Xi^+_{3/2}$	2070	1883	1862 ± 2 [95]	2016.53 ± 10.53
	$\Xi^0_{3/2}$				2020.51 ± 10.53
	$\Xi^-_{3/2}$				2023.12 ± 10.53
	$\Xi^{--}_{3/2}$				2024.37 ± 10.53

Let us examine how the $N^*(1685)$ mass varies when the Θ^+ mass shifts from the LEPS data to the DIANA measurement ($M_{\Theta^+} = (1538 \pm 2)$ MeV). To simplify this analysis, we disregard isospin symmetry-breaking effects. Under these conditions, the Θ^+ and N^* masses take the form:

$$\begin{aligned} M_{\Theta^+} &= \overline{M}_{\overline{10}} - 2m_s\delta\,, \\ M_{N^*} &= \overline{M}_{\overline{10}} - m_s\delta\,, \end{aligned} \tag{9}$$

where $\overline{M}_{\overline{10}}$ denotes the mass-splitting center of the baryon antidecuplet, determined by $\overline{M}_8 + 3/2I_2$ (see Ref. [77] for details). The parameter δ, defined as $\delta = -\alpha/8 - \beta + \gamma/16$, governs the mass splitting between members of the baryon antidecuplet [78].

Tables 3 and 4 summarize the numerical values of dynamical parameters. The parameter $c_{\overline{10}}$ represents the octet-antidecuplet mixing amplitude, corresponding to $c^B_{\overline{10}}$ in Eq. (8). Unlike previous studies [2, 92] which used $\Sigma_{\pi N}$ as an input, the present framework successfully predicts its value, notably yielding a relatively small magnitude. The fourth column displays

Table 3. The comparison of the dynamical parameters with those of Refs. [2, 92, 93]. The masses of the baryon antidecuplet members used as input are listed in the second row. The mass of the Θ^+ is taken from the LEPS data [48], *i.e.*, (1524 ± 5) MeV.

	Diakonov *et al.* [2]	Ellis *et al.* [92]	χQSM [93]	Present work I
Input masses	$N^*(1710\text{ MeV})$	$\Theta^+(1539 \pm 2\text{ MeV})$ $\Xi^{--}_{3/2}(1862 \pm 2\text{ MeV})$	$\cdots$ $\cdots$	$\Theta^+(1524 \pm 5\text{ MeV})$
$\Sigma_{\pi N}$	45 MeV*	73 MeV*	41 MeV	36.4 ± 53.9 MeV
I_1^{-1}	152.97 MeV	155.38 MeV	186.16 MeV	160.43 ± 50.26 MeV
I_2^{-1}	493.32 MeV	402.71 MeV	411.10 MeV	469.83 ± 56.71 MeV
$m_s\alpha$	-218 MeV	-605 MeV	-197 MeV	-262.9 ± 55.9 MeV
$m_s\beta$	-156 MeV	-23 MeV	-94 MeV	-144.3 ± 53.2 MeV
$m_s\gamma$	-107 MeV	152 MeV	-53 MeV	-104.2 ± 52.4 MeV
$c_{\overline{10}}$	0.084	0.088	0.037	0.0434 ± 50.0006
$N_{\overline{10}}$				1690 ± 511 MeV

Table 4. The comparison of the dynamical parameters with those of Refs. [2, 92, 93]. The masses of the baryon antidecuplet members used as input are listed in the second row. The mass of the Θ^+ is taken from the DIANA data [51], *i.e.*, (1538 ± 2) MeV.

	Diakonov *et al.* [2]	Ellis *et al.* [92]	χQSM [93]	Present work II
Input masses	$N^*(1710\text{ MeV})$	$\Theta^+(1539 \pm 2\text{ MeV})$ $\Xi^{--}_{3/2}(1862 \pm 2\text{ MeV})$	$\cdots$ $\cdots$	$\Theta^+(1538 \pm 2\text{ MeV})$
$\Sigma_{\pi N}$	45 MeV*	73 MeV*	41 MeV	37.5 ± 1.1 MeV
I_1^{-1}	152.97 MeV	155.38 MeV	186.16 MeV	160.43 ± 0.26 MeV
I_2^{-1}	493.32 MeV	402.71 MeV	411.10 MeV	475.49 ± 3.44 MeV
$m_s\alpha$	-218 MeV	-605 MeV	-197 MeV	-281.5 ± 6.30 MeV
$m_s\beta$	-156 MeV	-23 MeV	-94 MeV	-138.13 ± 3.09 MeV
$m_s\gamma$	-107 MeV	152 MeV	-53 MeV	-91.75 ± 2.08 MeV
$c_{\overline{10}}$	0.084	0.088	0.037	0.046 ± 0.0002
$N_{\overline{10}}$				1701 ± 5 MeV

results from the χQSM with all computed parameters. A comparison between Tables 3 and 4 reveals minimal variation in parameter values. The corresponding N^* masses are (1690 ± 11) MeV and (1701 ± 5) MeV, respectively, falling between the predictions of Refs. [92] and [2]. These findings suggest that the experimentally observed $N^*(1685)$ mass [48] supports the Θ^+ mass measurement from the LEPS Collaboration.

4. Widths of Θ^+ and $N^*(1685)$

As discussed by Praszałowicz [13], the narrow width is a peculiar but not unnatural feature of the Θ^+. The DIANA Collaboration consistently reported on a very small value for it, $\Gamma_{\Theta^+} = 0.34 \pm 0.10$ MeV [51], which makes searching for the Θ^+ tremendously difficult. A key prediction of Ref. [2] was that the decay width of the Θ^+ would be rather small[1], which distinguished it from previous works in the 1960s and 1970s. In this section, we will explicitly show that the small decay width of the Θ^+ is natural in the current approach.

The collective operator for the axial-vector constant is given as

$$\begin{aligned}\hat{g}_A \;=\; & a_1 D^{(8)}_{X3} + a_2 d_{pq3} D^{(8)}_{Xp}\,\hat{J}_q + \frac{a_3}{\sqrt{3}} D^{(8)}_{X8}\,\hat{J}_3 \\ & + \frac{a_4}{\sqrt{3}} d_{pq3} D^{(8)}_{Xp}\,D^{(8)}_{8q} + a_5 \left(D^{(8)}_{X3}\,D^{(8)}_{88} + D^{(8)}_{X8}\,D^{(8)}_{83} \right) \\ & + a_6 \left(D^{(8)}_{X3}\,D^{(8)}_{88} - D^{(8)}_{X8}\,D^{(8)}_{83} \right) , \end{aligned} \tag{10}$$

where a_1, a_2, and a_3 are the SU(3) symmetric terms, which correspond to G_0, G_1, and G_2 [2, 13], whereas a_4, a_5, and a_6 arise from the explicit SU(3) symmetry breaking. These dynamical parameters can either be determined using experimental data from hyperon semileptonic decays [98] or be computed within the χQSM [93]. As shown by Diakonov *et al.*, in the limit of small soliton size (nonrelativistic limit), the coupling constant $G_{\Theta NK}$ vanishes [2, 13], which explains why the width of the Θ^+ is naturally small.

The decay width of the Θ^+ depends on its mass. Figure 2 depicts the mass dependence of the decay width for $\Theta^+ \to KN$. When we use $M_{\Theta^+} = (1524 \pm 5)$ MeV, the width of the Θ^+ turns out to be $\Gamma_{\Theta^+} = (0.5 \pm 0.1)$ MeV, which is close to the DIANA result, $\Gamma_{\Theta^+} = (0.34 \pm 0.1)$ MeV. On the other

[1] Jaffe [96] pointed out a numerical mistake in deriving the decay width of the Θ^+ in the paper by Diakonov *et al.* [2]. If it is corrected, the Γ_{Θ^+} would become around 30 MeV. However, as Diakonov *et al.* refuted in Ref. [97], the refined analyses on the Γ_{Θ} showed that it is indeed small [78, 92]. As will be discussed in this section, more sophisticated analyses within the χQSM yielded a width of the Θ^+ smaller than 1 MeV. The smallness of the predicted Θ^+ decay width is a firm conclusion from the χQSM.

hand, if we use the mass from the DIANA data, $M_{\Theta^+} = (1538 \pm 2)$ MeV, we obtain $\Gamma_{\Theta^+} \approx 1$ MeV. Note that the prediction from the χQSM is $\Gamma_{\Theta^+} = 0.71$ MeV, which is also very small. Thus, both the current approach and the χQSM yield small values for the Θ^+ decay width.

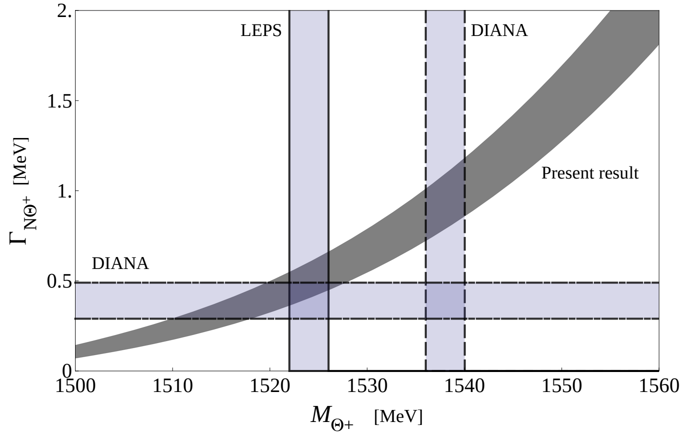

Fig. 2. The dependence of the decay width $\Gamma_{N\Theta^+}$ for the $\Theta^+ \to KN$ decay on M_{Θ^+}. The vertical shaded bars bounded with the solid and dashed lines denote the measured values of the Θ^+ mass with uncertainties by the LEPS and DIANA collaborations, respectively. The horizontal shaded region draws the values of the N^* mass with uncertainty taken from Ref. [94]. The sloping shaded region represents the present results of the M_{Θ^+} dependence of $\Gamma_{N\Theta^+}$.

5. A different summary

In remembering Maxim Polyakov, we are reminded of a physicist whose scientific conviction remained unwavering even in challenging times. The initial excitement following his 1997 prediction of the Θ^+ pentaquark with Diakonov and Petrov led to numerous experimental searches and theoretical works. However, the field reached a critical turning point in 2006 when the CLAS Collaboration at Jefferson Lab, using photoproduction experiments similar to those that had previously yielded positive results, reported on null results for the Θ^+. This, combined with null results from other high-energy facilities, led to a dramatic decline in light pentaquark research. Interestingly, a subsequent reanalysis by Amaryan *et al.* [54], including some members of the CLAS Collaboration, found evidence for the Θ^+ in $^1\mathrm{H}(\gamma, K^0_\mathrm{S})X$ via interference with ϕ-meson production, adding another perspective to the ongoing debate. The contrast between various experimental results, including the continued positive signals from DIANA ($\Gamma_{\Theta^+} = 0.34 \pm 0.10$ MeV) and LEPS collaborations, remains an intriguing puzzle in hadron physics.

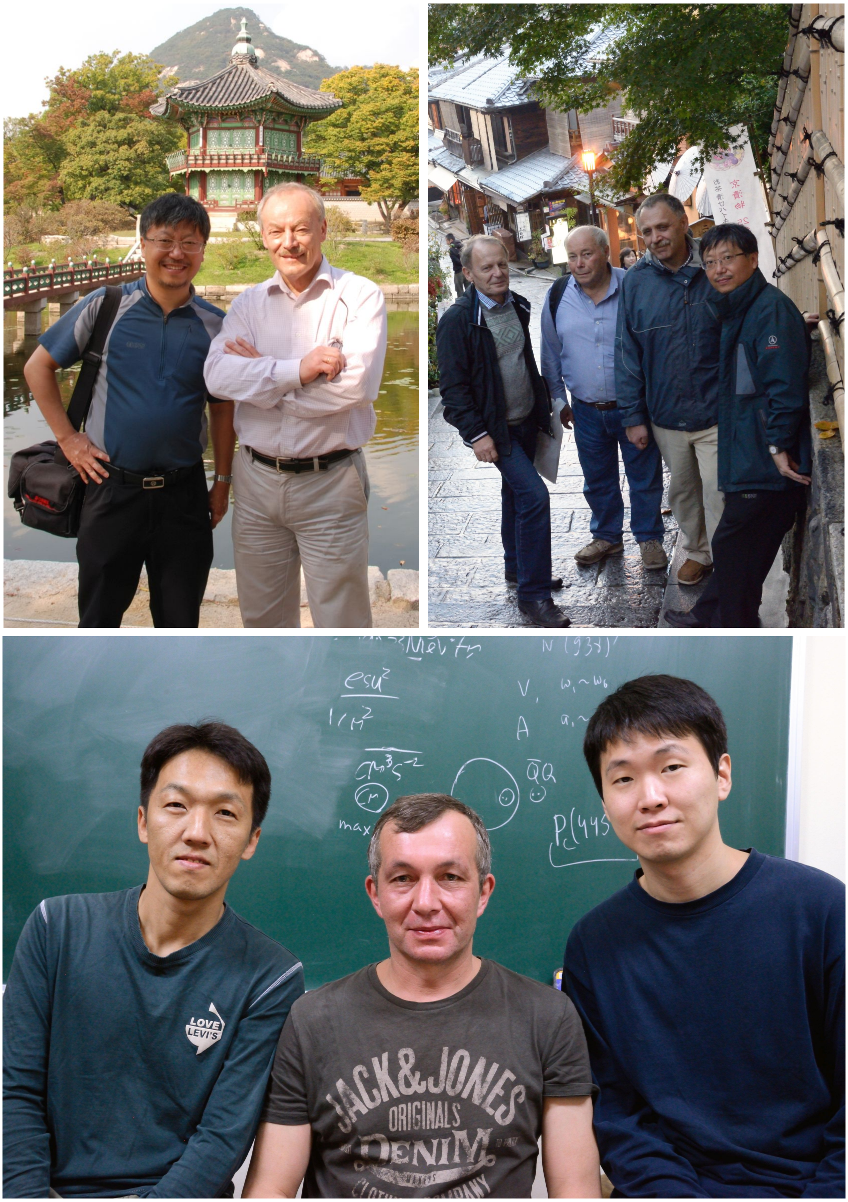

Fig. 3. Upper-left panel: H.-Ch. Kim (left) and Dmitri Diakonov (right) in Gyeongbokgung Palace, Seoul. Upper-right panel, from the left to the right: Anatoly Gridnev, Igor Strakovsky, Viktor Petrov, and H.-Ch. Kim in Kyoto. Lower panel: Maxim (in the middle) with his former Korean students, Ghil-Seok Yang (left) and Hyeon-Dong Son (right).

The photographs given in Figs. 1 and 3 included in this review capture not just the professional collaborations but also the warm friendships that characterized Maxim's approach to physics. They remind us of his Siberian hospitality and his belief in direct, honest scientific discourse — a tradition he traced to the Landau and Gribov school. His emphasis on physical understanding over rhetoric and his genuine openness to scientific debate exemplified the best traditions of theoretical physics. I include three more pictures in Fig. 3, showing the authors of the 1997 paper.

As new experimental groups prepare to search for pentaquark states, the questions Maxim grappled with remain relevant. His untimely passing leaves a void in the hadronic physics community, but his work continues to illuminate our path forward, particularly as we seek to understand the apparent contradictions between different experimental approaches to pentaquark searches. His legacy lives on in both the theoretical framework he helped develop and the scientific integrity he consistently demonstrated throughout his career.

I want to express special gratitude to Ghil-Seok Yang, a former student of Maxim Polyakov. I have worked with him on light and heavy pentaquarks for 20 years. A major part of the present work stems from our collaboration. I am also grateful to Igor Strakovsky for giving me the opportunity to write about Maxim. I am very thankful to Michał Praszałowicz who made invaluable comments on the decay width of the Θ^+. The present work was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Korean government (Ministry of Education, Science and Technology, MEST), grants No. 2021R1A2C2093368 and No. 2018R1A5A1025563. I would also like to acknowledge the long-term workshop on HHIQCD2024 at the Yukawa Institute for Theoretical Physics (YITP-T-24-02), during which I discussed pentaquark baryons with several participants, in particular with Atsushi Hosaka.

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