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Cite as: AIP Conference Proceedings **842**, 409 (2006); https://doi.org/10.1063/1.2220285

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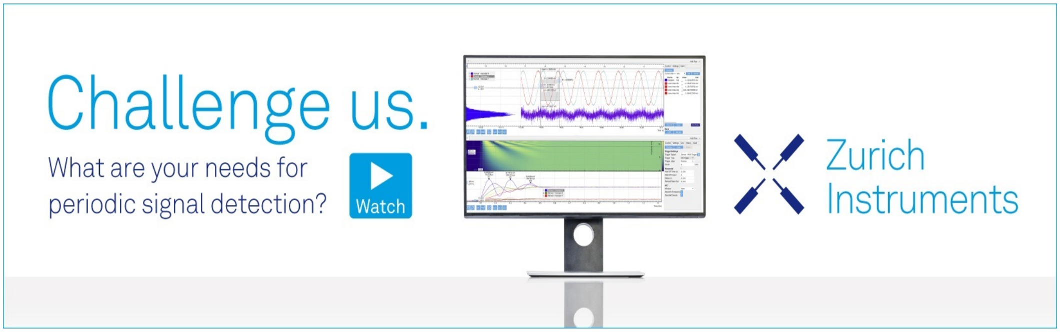

AIP Conference Proceedings **842**, 409 (2006); https://doi.org/10.1063/1.2220285

The Rise and Fall of Pentaquarks in Experiments.

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Abstract.
Experimental evidence for and against the existence of pentaquarks has accumulated rapidly in the last three years. If they exist, they would be dramatic examples of hadronic states beyond our well-tested and successful particle models. The positive evidence suggests existence of baryonic objects with widths of at most a few MeV, some displaying exotic quantum numbers, such as baryons with strangeness $S = +1$. The non-observations of these states have often come from reaction channels very different from the positive evidence channels, making comparisons difficult. The situation has now been largely clarified, however, by high-statistics repetitions of the positive sightings, with the result that none of the positive sightings have been convincingly reproduced. The most recent unconfirmed positive sightings suffer again from low statistics and large backgrounds. It seems that a kind of "bandwagon" effect led to the overly-optimistic interpretation of numerous experiments in the earlier reports of exotic pentaquarks.

Keywords: pentaquark
PACS: 14.20.-c,13.30.-a, 13.60.Rj

INTRODUCTION

This talk will discuss the experimental evidence for and against pentaquarks, in particular the "exotic" baryonic states that have charge and flavor quantum numbers that require a minimal valence quark configuration of four quarks and one anti-quark. The recent work in this field began with the first report [1], at the 2002 PANIC conference, of a narrow $S = +1$ at 1540 MeV decaying to K^+n. There are older chapters in the search for positive strangeness "Z" resonances [2] and of charmed strange pentaquarks [3] that we will omit here. In the three years since the announcement of a positive strangeness baryon, named the "Θ^+", an enormous amount of work has been done, seemingly by every particle physics collaboration in the world, to seek evidence for narrow pentaquark states. This led to the sightings for states identified as the Θ^+, the Ξ_5^{--}, the Θ_c^0, and the Θ^{++}. After an initial flurry of positive reports for these states, null results, that is, searches that led to no observed narrow exotic structures, started to dominate the field. As I will try to show below, from the perspective of the 2005 PANIC conference, there was a certain sociological "bandwagon effect" in 2003 and the first half of 2004 in which numerous groups rushed be part of the wave of positive sightings. The bandwagon lost momentum when measurements repeated with higher statistics gave negative results, and when numerous negative searches emerged in previously unexplored channels. While over 50 experimental papers discussing pentaquark searches can now be found in the literature, over the same time period there have been over 550 theoretical papers. Thus, the impact of pentaquark searches has been to renew interest in models of QCD which try to

CP842, *Particles and Nuclei,*
Seventeenth International Conference on Particles and Nuclei
edited by P. D. Barnes, M. D. Cooper, R. A. Eisenstein, H. van Hecke, and G. J. Stephenson

address the fundamental question of why nature prefers only the conventional 3-quark baryonic states and not more complex configurations such as pentaquarks.

What are pentaquarks? QCD does not explicitly forbid baryons with four quarks and an antiquark, or mesonic-like states two quarks and two anti-quarks. This was discussed in the context of bag models, for example, by Jaffe [4] and deSwart *et al.* [5]. In soliton models there were early discussions by, among others, Kopeliovich [6], Chemtob [7], and Walliser [8]. However, the recent interest in pentaquarks stems from bold predictions made by Diakonov, Petrov and Polyakov [9] in the context of a chiral-quark soliton model for an anti-decuplet of pentaquark states. They predicted a narrow ($\Gamma_{\Theta^+} \sim 15$ MeV) $uudd\bar{s}$ state, the Θ^+, close to $M = 1530$ MeV. The same model predicted seven non-exotic pentaquark baryons which could behave like ordinary N^* states or hyperons. The model also predicted a set of cascade-like ($S = -2$) states near 2070 MeV, two of which, the Ξ_5^{--} and the Ξ_5^{+} had the charge-flavor–exotic structures $ddss\bar{u}$ and $uuss\bar{d}$, respectively. In this model, the pentaquarks emerge as rotational excitations of the soliton, with $J^P = \frac{1}{2}^+$.

The initial experimental reports of states corresponding, perhaps, to this specific anti-decuplet prediction led to extensive theoretical re-evaluation of QCD models to shed additional light on pentaquark physics. For example, in a quark-model approach Jaffe and Wilczek [10] explored the possibility of di-quark attraction strong enough to cause new stable hadronic structures. In that model, the pentaquarks consist of two bosonic (ud) diquark pairs coupled via $L = 1$ to an anti-quark, with the lowest states having $J^P = \frac{1}{2}^+$. An octet of di-quark pentaquarks was predicted to accompany the anti-decuplet, and it was suggested that charm and bottom analogs to the Θ^+ might also be stable against strong decay.

The lattice community tried to find evidence for pentaquark structures, and results from a total of 10 groups have appeared [11]. In all those studies, the crucial point was to distinguish a simple KN continuum scattering state from a "bound" Θ^+ pentaquark structure. The results were conflicting, with equal numbers of results reporting a pentaquark structure as not, and with disagreement among the affirmative results regarding the spin and parity of the ground state.

EXPERIMENTAL EVIDENCE

A way of summarizing the various categories of pentaquark searches since October 2002 is given in Fig. 1. The table groups experiments by reaction type, and uses green (horizontal bars) or red (vertical bars) circles to show the experiments in each category that found positive or negative evidence, respectively, for pentaquarks. For example, in the first row are the experiments done with few-GeV real photons on deuterium or carbon. Four positive Θ^+ pentaquark sightings are entered, but then a recent negative result completes the row. The negative result in this reaction category was a high-statistics repetition (from CLAS at Jefferson Lab (CLAS-d2) [12]) of one of the previous positive sightings (also from CLAS at Jefferson Lab (CLAS-d1) [13]). The structure of the table is meant to suggest that pentaquarks in this category of reaction have likely been ruled out. As another example, the one positive Ξ_5^{--} measurement from NA-

49/CERN [14] is followed, on two rows of the table, by at least 10 negative results from either hadronic or electromagnetically induced reactions.

The intent of the table in Fig. 1 is also to show how a kind of "bandwagon" effect took place starting in late 2002, with a succession of positive pentaquark sightings from diverse collaborations. By the middle of 2004 a total of 14 positive sightings were reported. There was concern about the consistency of these reports, especially the somewhat discrepant reported mass values, and the generally poorly-understood backgrounds in the reported mass spectra. The rush of positive sighting then stopped, and from the middle of 2004 until late 2005 most of the reports were negative. As seen in the table, in many cases one can say that a given negative result essentially repudiates a specific previous positive sighting. Few experiments have been repeated under exactly identical experimental conditions, so there is room for continued debate in some cases. The remaining unchallenged positive findings (rows not ending in a red (vertical bars) marker) are becoming harder to reconcile.

This table is not exhaustively complete. For example, more experiments than are shown reported *not* seeing a Θ^{++} state, though rigorous upper limits were seldom given. Also, we omit the phenomenological studies that reanalyzed existing KN phase shift and scattering data to infer a maximum allowable width for the Θ^+. These led to estimates of $\Gamma_{\Theta^+} \simeq 1$ MeV for the allowable total width of the Θ^+ [15] [16] [17].

In the category of real GeV photons on nuclei, the initial report from LEPS/SPring-8 [1] used a carbon (scintillator) target; a subtle Fermi-motion correction was needed since only a K^+ and K^- were detected in the reaction $\gamma(N) \to K^+K^-X$. A follow-up experiment from LEPS/SPring-8 on deuterium [18] was performed under the same conditions as the carbon experiment. More evidence for the Θ^+ formation was shown at conferences, but that result is unpublished. The LEPS collaboration also reported a weak positive signal, from the same data set, in the exclusive channel $\gamma d \to \Lambda(1520)\ \Theta^+$ [19]. The identified $\Lambda(1520)$ tagged the strangeness of the Θ^+, but the signal sat on a large and steeply-sloped background. Stronger positive evidence for a Θ^+ was reported by CLAS/JLab [13] in an exclusive measurement on deuterium, $\gamma d \to pK^+K^-(n)$. A 4.6 to 5.8 σ signal was seen above a large background that was difficult to estimate quantitatively due to nuclear final state interaction effects. Both LEPS and CLAS suffered from unknown or poorly-known background distributions under their resolution- and statistics-limited signal peaks.

CLAS at Jefferson Lab repeated the measurement on deuterium in early 2004, and reported results in mid-2005 [12]. With six times the statistics, no Θ^+ peak was seen in the $\gamma d \to pK^+K^-(n)$ reaction, and a model-dependent upper limit of 4 to 5 nanobarns was set for a state at 1.54 GeV. The previous CLAS result, when fitted with a luminosity-scaled background shape from the higher statistics run, was reduced in significance to about 3σ. CLAS also did not see a signal in the $\Lambda(1520)\Theta^+$ final state, albeit the kinematic conditions were not the same as those at LEPS. On balance, there is no good strong experimental evidence left to suppose the existence of a Θ^+ produced in these channels.

In exclusive production by GeV-scale real photons on the proton, excitement was generated by the SAPHIR Collaboration at Bonn [20] when they reported a 300 nanobarn positive signal in the reaction $\gamma p \to \overline{K^0}\ \Theta^+ \to \pi^+\pi^-K^+(n)$. The strangeness of

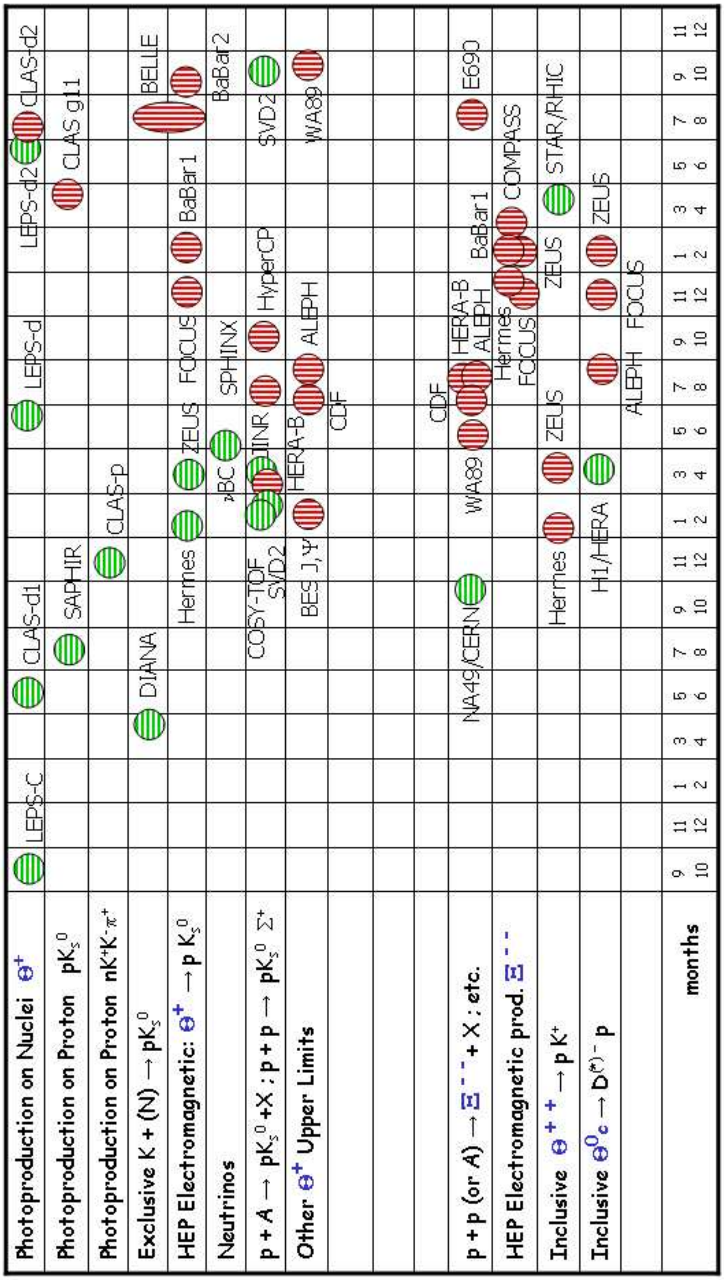

FIGURE 1. Time line of the experimental pentaquark searches from 2002 to 2005. Horizontal bars (green circles) designate claims of sighting, while vertical bars (red circles) designate reported non-observations.

the decaying K_S^0 was indeterminate, but the narrowness of the signal, $\Gamma < 25$ MeV, was believed to signal formation of the pentaquark. This same reaction was tested with much higher statistics at the same kinematics by the CLAS Collaboration [21]. No Θ^+ signal was found, and an integrated upper limit of 0.8 nb was set at 1.54 GeV, with similar results over a wide range of mass values and production angles.

A second channel of exclusive production on the proton was reported by CLAS [22], in $\gamma p \rightarrow \pi^+ K^- K^+ (n)$. The neutron was detected by missing mass, the pion was constrained to go into the forward hemisphere in the center of mass, and the K^+ from the putative pentaquark decay was constrained to be in the backward hemisphere. This combination of cuts was thought to enhance diffractive production of a high mass non-strange nucleon resonance which could then decay to a K^- and a Θ^+. A 7.8σ signal was reported. So far, this measurement has not been repeated at any other lab. It is perhaps the most convincing remaining candidate as of the beginning of 2006.

The ideal way to make a Θ^+ pentaquark that has a mass near 1.54 GeV is to scatter K^+ particles of about 430 MeV/c momentum from neutrons. Review of the low energy kaon scattering phase shifts revealed no signatures, but left open the possibility of excitation of a small, less than 1 MeV wide state [15][16][17]. The DIANA collaboration at ITEP used a slowing 850 MeV/c K^+ beam in a xenon bubble chamber to report a narrow signal at 1.54 GeV [23]. The detected final state of $K_S^0 p$ had no well-defined strangeness, but the initial K^+ did define the strangeness. In recent years there have been no high intensity low momentum kaon beams in the world to repeat this kind of measurement. To evade this problem, the Belle Collaboration at KEKB, searched for hadronic events stemming from identified K^+'s, produced in e^+e^- collisions, that interacted in detector elements near the collision point [24]. Their sensitivity was slightly better than that of the DIANA experiment, but they did not confirm the previous measurement. An upper limit given in terms of the width of the state was reported, $\Gamma_{\Theta^+} < 0.64$ MeV.

A second nearly ideal way to make a Θ^+ pentaquark is in the reaction $pp \rightarrow \Sigma^+ \Theta^+$, where the pentaquark decays to $K_S^0 p$. This avenue was followed by the TOF Collaboration at COSY/Jülich which reported [25] a 4 to 6 σ signal in this channel using a non-magnetic time of flight spectrometer. Unfortunately, their experimental background under the signal, like in many of the other positive sightings, was not calculable, and so had to be fitted with a polynomial. This leads to concern about the reliability of the signal-to-background estimation. Also, there was no hint of the Θ^+ band in a $\Sigma^+ p K^0$ Dalitz plot analysis. This measurement has not been repeated yet at COSY or any other laboratory, so it stands, at the present time, as a surviving candidate.

At much higher energies, one can consider pentaquark production in the fragmentation of quark systems from various targets. The HERMES Collaboration at HERA reported [26] a Θ^+ signal from quasi-real photons ($Q^2 \sim 0$) produced in positron scattering at 27 GeV on deuterium. It was a statistically weak signal, relying on background estimation from a standard Monte Carlo fragmentation model, but also invoking the presence of a number of poorly-characterized excited hyperon resonances, in addition to the putative Θ^+. At the other end of the Q^2 continuum, a Θ^+ signal was reported by the ZEUS Collaboration [27] at HERA from ep collisions near a c.m. energy of 310 GeV. A narrow bump appeared at 1.52 GeV above a quark fragmentation Monte Carlo background estimation, but only for $Q^2 > 20$ (GeV/c)^2. The signal was visible in both the

$K_S^0 p$ and the $K_S^0 \overline{p}$ combinations, which, while neither tags the strangeness of the signal uniquely, does hint at the formation of both Θ^+ and $\overline{\Theta^+}$. Unfortunately, the signal resides very near the steeply-sloped phase-space background for the detected final state, such that the significance of the signal hinges crucially on the reliability of the background Monte Carlo model. Furthermore, a second bump near the putative Θ^+ was seen, and this was ascribed to a poorly-known Σ hyperon resonance, and such hyperon bumps are otherwise unseen in high energy experiments.

These two experiments in high energy lepton scattering can be contrasted with the much higher statistics measurements from the BaBar Collaboration at SLAC [28]. In that measurement, beam halo electrons and positrons scattered from the beam pipe surrounding the interaction region, resulting in nuclear scattering of the leptons from beryllium. Such events are dominated by the lowest Q^2's, and thus are comparable to the kinematics of the HERMES measurement. There was no hint of a Θ^+ in the BaBar $K_S^0 p$ spectrum, contradicting the previous experiment. The comparison of BaBar to ZEUS is less significant since the latter result was for $Q^2 > 20$ (GeV/c)^2; indeed, ZEUS saw no signal at lower Q^2. We also note that BaBar did not see a signal for the Θ^+ or any of the other pentaquark states in $e^+ e^-$ collisions not related to "beam pipe" scattering, and set upper limits about an order or magnitude below the production of ordinary baryons near the candidate mass values [29].

Mining old data for new phenomena, five neutrino bubble chamber experiments from CERN and Fermilab were combined to report a narrow peak of a few dozen $K_S^0 p$ events at 1.53 GeV [30]. There was a clear excess of events above the mixed-event background, not only at the location of the putative pentaquark but also at higher masses. Thus, it is possible that the estimated background was not understood well enough to reliably claim the presence of a specific new signal at 1.53 GeV.

In scattering hadronic probes at high energy from nuclear target, a positive signal for the Θ^+ decaying to $K_S^0 p$ was reported by the SVD Collaboration, using 70 GeV protons in a fixed-target arrangement at a c.m. energy of about 11.5 GeV. Their initial report [31] was supported by a more recent [32] detailed analysis which increased their pentaquark signal by a factor of about 8. The signal in the $K_S^0 p$ mass spectrum comprises about 300 events per channel, with a substantial background under the peak that was modeled using mixed events and standard Monte Carlo. The statistics of this measurement must be contrasted to the results of WA-89 Collaboration for the scattering of a 340 GeV/c Σ^- beam from carbon and copper [33]. At these high energies it is hard to imagine that the beam energy, probe, or target material could make much difference to the production of pentaquarks. Thus, the featureless 40,000 counts per channel in the WA-89 spectrum strongly suggests that hadronic production of the Θ^+ has not occurred. The SPHINX Collaboration at IHEP had also looked using 70 GeV protons on carbon for a Θ^+ signal with a null result [34]. They were able to reconstruct decay channel $K_S^0 p$, but also had results for $K_L^0 p$ and $K^+ n$. Their upper limits were in the range of 30 nb/nucleon, and a production ratio of $\Theta^+ \; \overline{K^0}$ to $\Lambda(1520)K^+$ of less than 0.02. A further negative result for 800 GeV protons on a carbon target was reported by HyperCP at Fermilab [35]. Their upper limit was given as less than 0.3% Θ^+ production of all reconstructed $K_S^0 p$ events. Finally, a negative result was reported by HERA-B [36] for the interaction at 41.6 GeV c.m. energy of protons on several nuclear targets. They set modest upper limits for Θ^+

production of less than 16 μb/N and less than about 12% relative to the $\Lambda(1520)$. Thus, despite the recent positive result reported by SVD-2, the evidence is greatly against the production of Θ^+ pentaquarks in high energy hadronic production.

Further non-observations of the Θ^+ were reported for J/ψ decays involving $\Theta^+ \to K_S^0 p$ from BES [37], for $p\overline{p}$ collisions from CDF [38], and from events in e^+e^- collisions at the Z pole from ALEPH [39]. The significance of these results in relation to the positive observations at low energies is difficult to estimate, since the production mechanism of exotic pentaquarks is, well, exotic. Nevertheless, these results add some weight to the conclusion that these states have in fact not been seen.

In the theoretical models mentioned earlier [9] [10], the other exotic pentaquarks that were predicted were two cascade-like ($S = -2$) states in the mass range of 1.75 to 2.07 GeV. The NA-49 Collaboration at CERN found evidence [14] for narrow states at 1.86 GeV in pp collisions at 17 GeV c.m. energy, detected via decays such as $\Xi_5^{--} \to \Xi^- \pi^-$. (Note that the Particle Data Group calls this state the $\Phi(1860)$.) The close agreement of the predictions with this experimental result was very exciting, especially in view of the previous seemingly accurate predictions of the mass of the Θ^+. However, a deluge of contrary experimental results followed this one positive claim for a cascade pentaquark. At least ten results have been released which repudiate the existence of the states seen by NA-49: from WA-89 [40], CDF [38], HERA-B [36], ALEPH [39], HERMES [41], FOCUS [42], BaBar [43], ZEUS [44], COMPASS [45], and E690/Fermilab [46]. In general, the negative reports have much higher statistics than the original positive report, and came from pp, ep, pA, and γA experiments. Upper limits relative to production of the well-known $\Xi(1530)$ state were typically an order of magnitude below the NA-49 observation. Thus, there is really no chance left that these exotic pentaquarks candidates exist at measurable production levels.

The H1 Collaboration at HERA reported evidence [49] in ep collisions for a narrow anti-charmed baryon dubbed the Θ_c^0, which would have a minimal quark configuration of $uudd\overline{c}$. The state had a mass of 3.099 GeV, was as narrow as the experimental resolution, and detected via the decays $D^{*-}p$ and $D^{*+}\overline{p}$. It was reported to contribute about 1% of the D^* production rate in DIS. As in many of the other pentaquark searches, the signal comprised two or three "high" channels above a very substantial background. A 5.4σ significance was claimed for the high-count region. Much higher statistics negative results were subsequently reported in the same final states by ZEUS [47], FOCUS [48], and ALEPH [39]. No other positive sightings have come out.

If the Θ pentaquark were an isovector object, not the isoscalar predicted in most models, then other charge states exist, such as a Θ^{++}. The decay of this state to K^+p is especially easy to look for. Whereas many non-sightings have been mentioned in the pentaquark literature, a recent result from the STAR Collaboration at RHIC claims [50] a narrow state decaying to K^+p in deuteron-gold collisions at 200 GeV NN c.m. energy, with a 4.2σ significance. The state sits atop a very large but smooth mix-event background, but unfortunately also sits next to an equally large bump that is attributed to K/π particle identification errors. Confirmation of this structure and its interpretation are clearly needed.

CONCLUSIONS

In summary, after three years of intense activity, pentaquarks have come and gone. In this paper/talk we have not had time or space to dwell on many specifics of any of the experiments, but the overall trends are very consistent. Most of the positive sightings have been contradicted or placed in doubt by better measurements. The remaining candidates have no common thread to unify their phenomenology. Most important, no single truly convincing positive measurement claim has appeared. Recent new candidates suffer (again) from low statistics and poorly-understood backgrounds. As was shown in this paper, there was a rush of positive sightings between late 2002 and mid-2004. From that time forward almost all experiments showed null results for detection of Θ, Ξ_5 and Θ_c pentaquarks. Thus, one can conclude that a "bandwagon" rush of over-optimistic positive sightings was in effect initially, but now the lack of convincing evidence for narrow exotic pentaquarks is overwhelming.

Acknowledgments: The collection of information for this talk and paper was facilitated by discussions with V. Burkert, C. Meyer, D. Tedeschi, K. Hicks, and P. Stoler.

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