A POSSIBLE EXOTIC BARYON RESONANCE

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I. Introduction

The well-established baryon states can be understood as combinations of three valence quarks. In this discussion, we confine ourselves to baryon states constructed from combinations of u, d, and s quarks. The three-quark combinations are members of SU(3) singlets, octets, and decuplets. Baryon states that cannot be constructed with triplets of u, d, and s quarks are called exotic.

Do there exist in nature baryon states constructed from more complicated quark configurations? The simplest might consist of four quarks plus an antiquark. In a 1997 paper [1], Diakonov *et al.* proposed, on the basis of a chiral soliton model, the existence of a low-mass anti-decuplet of such baryons, with spin 1/2 and even parity, and with specific estimates for the masses and widths. Figure 1, from their paper, shows this proposed anti-decuplet. The baryons at the three corners of the triangle are exotic: their isospin and strangeness cannot be obtained by any triplet combination of u, d, and s quarks. The other baryons of the anti-decuplet are made up of combinations such as, for example, $uudd\overline{d}$ and $uuds\overline{s}$ (relevant to the charged $N(1710)$ in Fig. 1). These two combinations have the same isospin and strangeness as uud, and the corresponding baryons are therefore not exotic. Diakonov *et al.* estimated the masses and widths of the four isospin multiplets in the anti-decuplet of Fig. 1. They assumed equal mass spacings between multiplets, with a calculated spacing of 180 MeV. Associating the $S = 0$ isospin doublet with the $N(1710)$, an $I = J = 1/2$, P-wave πN resonance listed in our Tables, they predicted a mass of 1530 MeV for the $S = +1$ exotic Z^+ isosinglet. They also estimated its total decay width to be 15 MeV or less.

Before 2003, there was no evidence for a narrow $S = +1$ baryon resonance, but that situation has now changed. In 2003, several groups searched old or new data for evidence of a K^+n or K^0p resonance in the neighborhood of the predicted 1530 MeV and reported positive results. On the other hand,

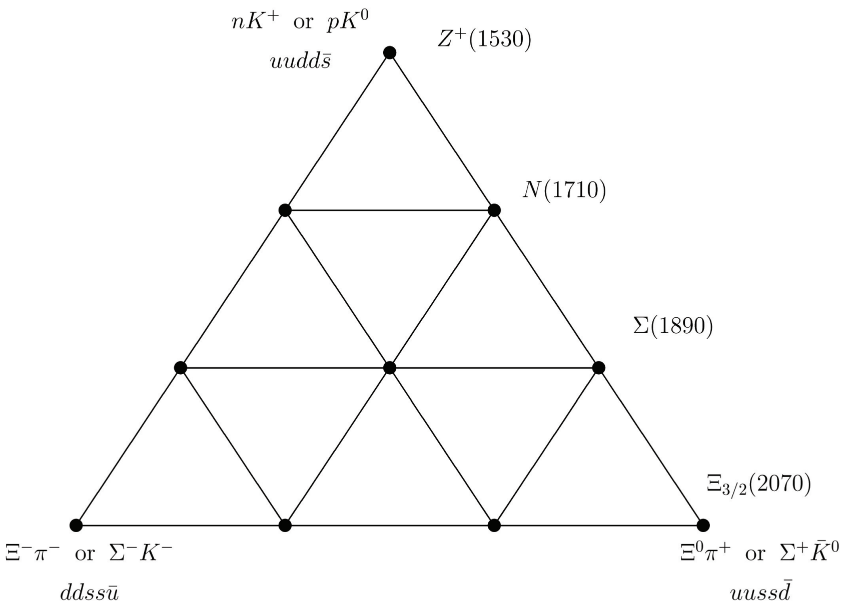

Figure 1: Proposed anti-decuplet of baryons (from [1]).

attempts to find this exotic state in other fairly extensive older published data have so far yielded no supporting evidence. We first consider the new positive results, and then review some of the relevant older information. One point of nomenclature: the Z^+ is now universally called the Θ^+.

II. Recent results

We discuss the results from seven different experiments. Five are photo- or electroproduction experiments using carbon, deuterium, or hydrogen targets, one is a K^+n charge-exchange experiment in a liquid-xenon bubble chamber, and one involves a compilation of neutrino bubble-chamber data with hydrogen, deuterium, and neon fills. As an example, we show in Fig. 2 the nK^+ mass spectrum from the first of two CLAS photoproduction experiments discussed below [2]. The structure at 1540 MeV is interpreted as a possible Θ^+ signal with a significance of 5.2 σ.

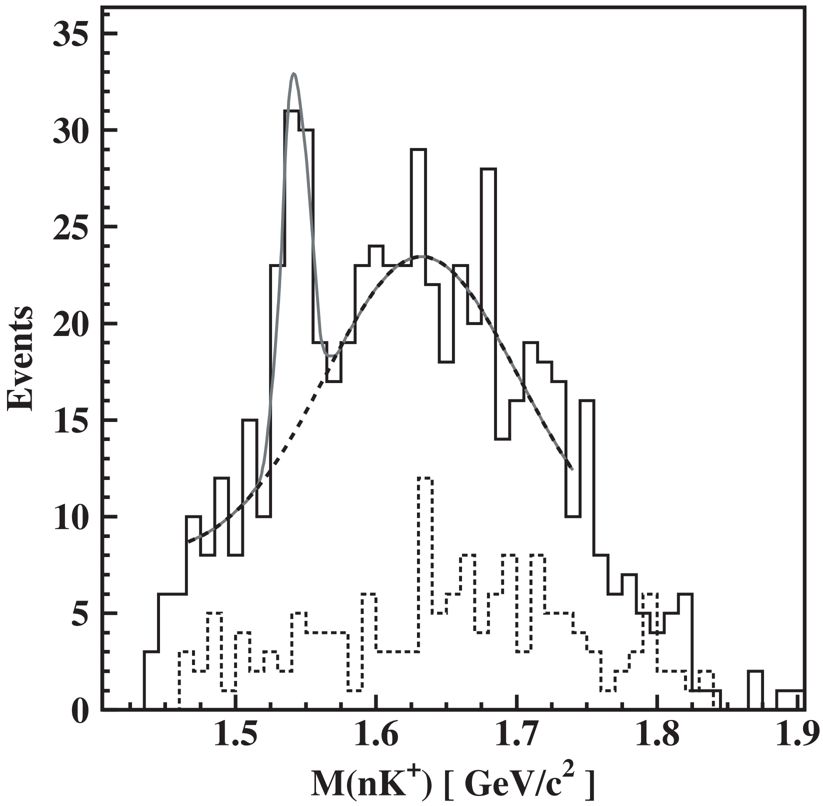

Figure 2: Invariant nK^+ mass spectrum from the reaction $\gamma d \to K^+K^-pn$ after cuts. The dotted histogram shows events associated with $\Lambda(1520) \to K^-p$ production (from [2]).

The LEPS experiment — The LEPS experiment [3] was carried out at the Laser-Electron-Photon facility at the Spring-8 Synchrotron Radiation Facility in Japan during 2000–2001. A photon beam with tagged energies between 1.5 and 2.4 GeV was incident on a scintillator target; for the Θ^+ search, the reaction $\gamma n \to nK^+K^-$, with carbon from the scintillator as the neutron target, was identified and measured in the LEPS spectrometer. The goal was to search for a nK^+ mass enhancement. Cuts were made to remove a large number of $\phi \to K^+K^-$ decays and possible backgrounds from $\gamma p \to pK^+K^-$ in the same carbon target. Corrections were made for the Fermi momentum of the target nucleon, relevant to the reconstruction since the final-state neutron is not detected. After cuts, the final sample consists of 109 events. There is a peak at 1540 MeV, consisting of 19 events above a background of 17. The significance is claimed to be 4.6 σ, the mass 1540 ± 10 MeV, and the width less than 25 MeV at 90% confidence.

The DIANA experiment — The DIANA experiment [4], run in 1986, was a xenon bubble-chamber exposure to a K^+ beam. The K^+ momentum at the bubble-chamber entry was 750 MeV/c, decreasing through ionization loss all the way to rest at the back of the chamber. Only those interactions produced by K^+ of momenta below 550 MeV/c were considered in the analysis, which focused on charge-exchange events, $K^+\mathrm{Xe} \rightarrow K^0_S pX$, with the K^0_S decaying into $\pi^+\pi^-$. After cuts to remove low-momentum protons and K^0_S, and cuts on K^0_S and proton directions (said to reduce the effects of rescatterings in nuclear matter), a sharp peak in the pK^0_S mass spectrum at 1539 ± 2 MeV, consisting of a signal of 29 events over a background of 44 events, was observed. The quoted statistical significance is 4.4 σ, and the width upper limit is 9 MeV.

The CLAS experiments — The first of the CLAS experiments [2], run in 1999 at Jefferson Lab, studied the nK^+ mass spectrum from the reaction $\gamma d \rightarrow npK^+K^-$, produced by a tagged photon beam of energies between 1.5 and 2.9 GeV. The events of interest are really $\gamma n \rightarrow nK^+K^-$, but reconstruction requires a detectable proton; hence only events with a rescattering that changes the spectator into a detectable proton are useful. With removal of $\phi \rightarrow K^+K^-$ and $\Lambda(1520) \rightarrow pK^-$ events, and an imposed upper limit of 1 GeV/c on the K^+ momentum, the spectrum shown in Fig. 2, with a signal of 43 events over a background of about 54 events, is observed. The mass is 1542 ± 5 MeV, the quoted significance is 5.2 σ, and the observed width of 21 MeV is consistent with the instrumental resolution.

Another CLAS experiment [5] studied the reaction $\gamma p \rightarrow n\pi^+K^+K^-$, a four-body final state, with photons of energies between 3 and 5.5 GeV. After a ϕ mass cut, the nK^+ mass distribution for 14,000 events shows no significant structure.

To enrich the sample, angular requirements that select events with forward π^+ and backward K^+ are imposed. These cuts remove about 95% of the events, leaving a peak in the nK^+ mass at 1555 ± 10 MeV. The fit yields a signal of 41 events over a background of about 35 events, with a quoted significance of 7.8 σ. The observed width of 26 MeV is consistent with the resolution.

The SAPHIR experiment — The 1997–1998 data from the SAPHIR experiment [6], run at the ELSA facility in Bonn, allow study of the reaction $\gamma p \to nK^+K^0_S$, with an incident tagged photon beam with energy between 0.9 and 2.6 GeV. To enhance the Θ^+ signal, a requirement that $\cos\theta_{\rm cm} > 0.5$, where $\theta_{\rm cm}$ is the angle between the beam and the K^0_S in the center of mass, is imposed. A signal of about 55 events over a background of about 56 is observed in the nK^+ mass spectrum at a mass of $1540 \pm 4 \pm 2$ MeV. The quoted significance is 4.8 σ, and the width is less than 25 MeV. Because there is no significant signal in the pK^+ spectrum observed in a separate experiment to study $\gamma p \to pK^+K^-$, the authors conclude that the Θ^+ must have $I = 0$.

A compendium of neutrino experiments — Asratyan *et al.* [7] have analyzed a database of some 120,000 ν and $\overline{\nu}$ charged-current events from the BEBC (CERN) and 15-foot (Fermilab) bubble chambers; the fills were hydrogen, deuterium, or neon. Some of the runs had mean incident energies of about 40 GeV and others about 110 GeV. The authors looked for final states with a proton (momentum between 300 and 900 MeV/c), and a K^0_S decay, both originating from the same vertex. The goal was to search for evidence of the Θ^+ in the pK^0_S mass spectra. A signal consisting of an excess of about 27 events over a background of about 8 events, at 1533 ± 5 MeV, was observed in the combined neon and deuterium data. The quoted significance is 6.7 σ, and the width is less than 20 MeV. There is one concern here: the K^0_S can have $S = +1$ or -1, and there are numerous $S = -1$ baryon resonances. The authors argue that, since there is no established $S = -1$, $I = 1$ narrow resonance near 1530 MeV, the observed structure must be taken as evidence for the Θ^+.

The HERMES experiment — In the HERMES experiment [8], a 27.6 GeV positron beam from the HERA storage ring is incident on a deuterium target in a search for Θ^+ in quasi-real inclusive photoproduction. The analysis selects final states with a proton and $K^0_S \to \pi^+\pi^-$ decay. In the resulting pK^0_S mass spectrum, an enhancement at a mass of $1528 \pm 2.6 \pm 2.1$ MeV is observed. Depending on the background model, the significance is said to be 4-to-6 σ and the width may be larger than expected from just the measurement uncertainty of 4.3-to-6.2 MeV (one standard deviation).

III. Information based on earlier data

There are a number of old experiments that may be relevant to the search for a Θ^+. We consider three sets of experiments:

(1) Studies of K^+p and K^+d interactions leading to $KN\pi$ final states. One looks for an enhancement in nK^+ and pK^0 mass distributions.

(2) Studies of π^-p interactions leading to $K\overline{K}N$ final states, again looking for structure in the KN mass distributions.

(3) Measurements of K^+d total and charge-exchange cross sections as functions of incident momentum, looking for a cross section peak in the neighborhood of 440 MeV/c.

K^+p and $K^+d \to KN\pi$ — One might expect that an $S = +1$ initial state would increase the likelihood of producing an $S = +1$ resonance in the final state. Published results for the reactions $K^+p \to pK^0\pi^+$, $pK^+\pi^0$, and $nK^+\pi^+$, studied in bubble chambers at incident momenta of 960, 1200, 1210, 1290, 1360, 1380, 1520, 1585, 1690, and 2650 MeV/c [9–12], have been examined with some care. In most cases, only Dalitz plots are available, but Berthon *et al.* [12] also supplies pK^0_S mass spectra with very substantial statistics. In these final states, the $K^*(892)$ and $\Delta(1232)$ dominate, and most features of the KN spectra are simply reflections of these resonances. Study of all the available Dalitz plots, especially away from the known resonance bands, shows no indication of a population increase near a pK^0 or nK^+ mass of 1540 MeV. Figure 3 shows some representative Dalitz plots, with the diagonal lines corresponding to a 1540 MeV KN resonance. For a strongly

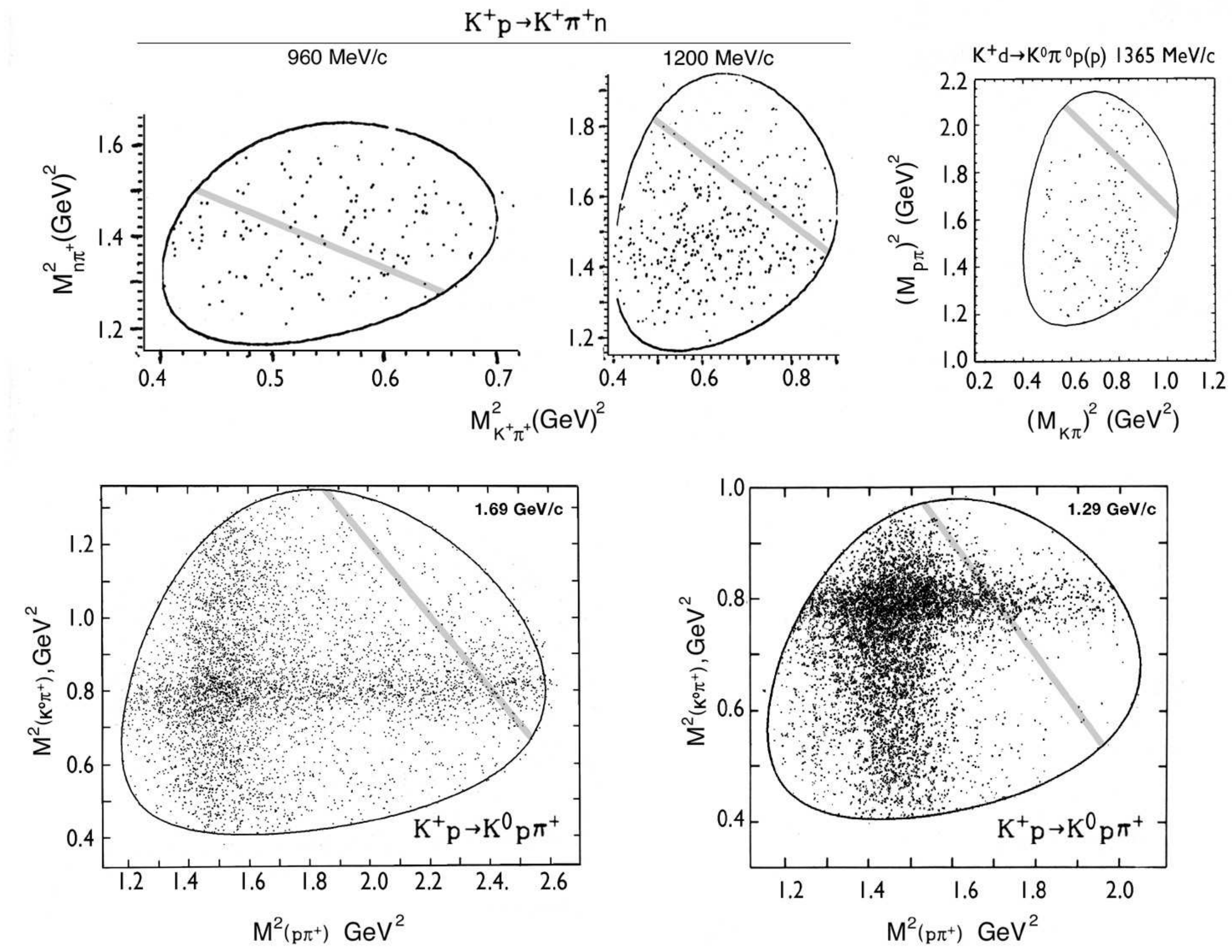

Figure 3: Dalitz plots for $K^+N \rightarrow KN\pi$ reactions studied in hydrogen and deuterium bubble chambers. References, going clockwise starting at upper left, are [9], [9], [13], [12] and [12]. The diagonal lines show where one would expect to see the $\Theta(1540)^+$.

decaying spin-1/2 state, the distribution of points along the lines should be uniform.

The Berthon *et al.* pK^0 mass spectra [12] show no indication of structure near 1540 MeV for incident momenta of 1210, 1290, 1380 MeV/c, but there is just a hint at 1690 MeV/c. Inspection of the corresponding Dalitz plot, however (see Fig. 3), indicates that any small population excess is likely related to overlap with the K^* resonance band. Similarly, the $K^+d \rightarrow KN\pi(N)$ Dalitz plots (see Fig. 3) from Hirata *et al.* [13] are also dominated by the same known resonance bands.

It is important to note that these bubble-chamber data have no acceptance issue, and that they have not been subjected to any cuts, unlike the claimed signal populations, where cuts have been made that enhance the Θ^+ signal relative to background.

$\pi^- p \rightarrow nK^+K^-$ and $pK^0_S K^-$ — Dahl at al. [14] used the Berkeley 72-in hydrogen bubble chamber to study the reactions $\pi^- p \rightarrow nK^+K^-$ and $\pi^- p \rightarrow pK^-K^0_S$ at momenta from 1.5 to 4.2 GeV/c. Their paper provides the relevant nK^+ and pK^0_S mass spectra, as well as Dalitz plots for three momentum groupings: 1.6–2.3, 2.9–3.3, and 3.8–4.2 GeV/c. Of the six relevant mass spectra, only one, nK^+ at 3.8–4.2 GeV/c, has the slightest hint of structure at low mass, but that structure is actually centered at about 1600 MeV with a width of roughly 200 MeV. There is simply no evidence in these data for a narrow KN resonance at 1540 MeV.

K^+d cross section data — An $I = 0$ KN resonance should manifest itself through increases in the K^+n charge-exchange and total cross sections at the resonance cm energy near 1540 MeV, corresponding for a neutron at rest to an incident K^+ momentum of 442 MeV/c. Since free-neutron targets are not available, K^+d cross-section measurements are required, and proper account must be taken of the Fermi momentum of the bound neutron. The distribution of the Fermi momentum in deuterium peaks near 50 MeV/c, and for a fixed incident K^+ momentum leads to a cm energy distribution with a full width of about 30 MeV. This number is, as shown below, much larger than any reasonable estimate of the Θ^+ width, and also is larger than the typical spread of incident momentum at any measurement point.

It is straightforward to calculate the resonance cross section averaged over the Fermi momentum distribution, as determined by the deuteron wave function. The result can be written as $\sigma_R = AB_iB_f\Gamma$, where B_i and B_f are the initial and final Θ^+ branching ratios relevant to the reaction under study, and Γ

is the full width. The coefficient A is the product of several factors, including the result of the Fermi-motion averaging process. For an incident K^+ momentum close to the resonant value for a stationary neutron target (442 MeV/c), and for a Θ^+ having spin 1/2 and isospin 0, the value of A is 3.6 mb/MeV [15].

We first apply this result to K^+d charge exchange, $K^+d \to K^0pp$, using the measurements from Slater *et al.* [16] at incident momenta of 376 and 530 MeV/c, and Damerell *et al.* [17] at 434, 526, and 604 MeV/c. The 434 MeV/c measurement is close to the resonance value, and the others are sufficiently distant that, even with the Fermi smearing, their resonance contributions are small. We estimate the resonance part of the 434-MeV/c cross section by subtracting from it a background estimated from interpolations and extrapolations of the cross sections at the other momenta. These subtractions yield numbers smaller than the estimated errors of 0.3 mb. There is therefore no evidence for a significant resonant contribution, and we estimate a conservative upper limit for σ_R of 1 mb. Here $B_i = B_f = 1/2$ in the above formula, and we deduce an upper limit for Γ of 1.1 MeV.

A similar analysis can be applied to the K^+d total cross section, using the data of Bowen *et al.* [18] at 366, 440, and 506 MeV/c. The 440 MeV/c point is very close to the resonance value, and the other two points are sufficiently distant to avoid the inclusion of resonance contributions arising from Fermi smearing. Subtraction of a linearly interpolated background cross section from the measured value at 440 MeV/c leads to an excess of 0.6 ± 0.3 mb. The fact that this difference deviates from zero should not be taken as evidence for the Θ^+: it can simply reflect deviation from linearity in the momentum dependence of the cross section. We take 1.5 mb as a conservative upper limit to the resonance cross section. Here B_i=1/2 and B_f =1, and the upper limit on Γ is 0.8 MeV.

Finally, we consider the $I = 0$ KN total cross sections reported by Bowen *et al.* [18] and Carroll *et al.* [19] at 440 MeV/c, and take the even more conservative approach of considering the full cross section at that momentum as resonant.

The Carroll and Bowen measurements disagree by about 3 mb, and we use Carroll's larger value of 13 mb. With $B_i = B_f = 1$, the upper limit for Γ is 3.6 MeV.

These width limits are predicated on the Θ^+ mass being in the range of 1533–1543 MeV, corresponding closely to incident momenta at which the K^+d charge-exchange and total cross sections have been measured. For masses of 1528 or 1548 MeV, the upper limits would increase by a factor of 1.6.

IV. Width estimate from xenon experiment

The results of the DIANA xenon charge-exchange experiment [4] have been analyzed by Cahn and Trilling [15] on the assumption that, near the resonance, one is observing charge exchange on a single nucleon. Associating the observed signal and background populations with resonant and non-resonant charge-exchange cross sections, they deduce a Θ^+ width of 0.9 ± 0.3 MeV, where the quoted error is statistical. The systematic uncertainty is difficult to evaluate.

V. Results from partial-wave analysis

Motivated by the newly reported results, Arndt *et al.* [20] have recently reanalyzed K^+N scattering data in the 1540 MeV cm energy region. They have considered possible structure not only in the P_{01} partial wave, but also in other S, P, and D waves. An immediate result was that the addition of resonances of widths above 5 MeV resulted in an enormous increase in the χ^2 of their fit to data. Indeed, they found no χ^2 improvement in their fit from the addition of resonances in S, P, or D waves unless the inserted structures had widths of 1 MeV or less. They conclude that Θ^+ widths larger than a few MeV are excluded, but that the existence of a Θ^+ in the P_{01} state with a width of 1 MeV or less is possible. These results are stronger than, although consistent with, a 6-MeV upper limit given by Nussinov [21] and a 5-MeV limit by Haidenbauer and Krein [22], and are consistent with the limits quoted in Secs. III and IV above.

VI. Comments on all these results

What can we conclude from these various results and observations? One general principle should apply: For claims of major new discoveries, the burden of proof is greater than for research results that fall within the boundaries of what is already established. Has this burden been met well enough to claim the discovery of an exotic baryon resonance?

Measured in terms of claimed numbers of standard deviations, the results are impressive. In some cases [5, 6, 7], inspection of the published plots suggests that the backgrounds may be somewhat underestimated (background fits seem to be normalized below the observed backgrounds), reducing perhaps the real significance of the results. Nevertheless, there are substantial indications that something interesting is being observed. However, that something seems to behave rather differently from the known non-exotic resonances. As one example, the $\Lambda(1520)$ decays by D-wave to $\overline{K}N$ with a partial width of 7.2 MeV, much larger than the upper limits based on measured cross sections and partial-wave analyses for the presumed P-wave $\Theta(1540)^+$.

There are some further concerns about the new evidence for the Θ^+. In most cases, the signal does not appear in a significant way until various cuts are made, often reducing the data sample by a large factor. Because all but the xenon and neutrino experiments involve spectrometers of finite acceptance, it is difficult for the reader of these papers to know what role kinematics and reflections from other resonances may have played in determining the results, especially since the cuts were likely chosen to optimize observed signal to background.

One of the most powerful tools for understanding resonances in three-body final states has been the use of Dalitz plots to study correlations and reflections, yet there are no published Dalitz plots in any of the new papers that involve three-body final states [2, 3, 6]. The possible importance of reflections has been emphasized in a recent paper by Dzierba *et al.* [23].

In three of the papers, the Θ^+ production is from a nucleus (carbon, xenon, or neon): the decay products may be created inside the nucleus, and may further interact before leaving the nucleus, raising some uncertainties about the interpretation of the final state. In short, most of the new papers are relatively brief, and yet, given the potential importance of the results, the work cries for more complete description and discussion.

There is the further problem that there seems to be no evidence for the Θ^+ in the rather extensive existing K^+N charge-exchange and total cross section data, in the $KN\pi$ and $K\overline{K}N$ final states produced by incident kaons and pions over a range of energies, and in the results of K^+N partial wave analyses. All the observations may be consistent with a Θ^+ having a width of 1 MeV or less, but then there are two further questions: Why the very small width for a strong decay, and why is the very narrow Θ^+ so readily produced in photoproduction experiments?

There is one other tantalizing piece of information. Alt *et al.* [24] have recently claimed to see, at the 4 σ level, another exotic baryon, an $S = -2$, $Q = -2$ $ddss\bar{u}$ state (see the lower left corner of Fig. 1) decaying into $\Xi^-\pi^-$ with a mass of 1862 ± 2 MeV and a width of less than 18 MeV. This mass agrees with neither the Diakonov *et al.* prediction of 2070 MeV [1] nor a later prediction of 1750 MeV from Jaffe and Wilczek [25]. Nevertheless, this observation is additional support for the existence of exotic baryons.

VII. Future Needs

What experiments do we need to establish fully the Θ^+, recognizing the fact that its width may be very small? One can suggest two experiments:

(1) Confirmation with high statistics, much improved effective mass resolution, and excellent particle identification, of the photoproduction results, through study of such reactions as $\gamma p \to nK^+K^0_S$, $\gamma n \to pK^0_S K^-$, and $\gamma n \to nK^+K^-$.

(2) Measurement in the 400–500 MeV/c incident momentum range of the $K^+d \to K^0_S p(p)$ charge-exchange cross section as a function of the final-state $K^0_S p$ mass. This requires measurement of the K^0_S decay and reconstruction of the $K^0_S p$ mass with the best possible resolution, in order to demonstrate resonant

behavior undiluted by target Fermi motion or beam-momentum spread.

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