Letter of Intent

Search for the Pentaquark

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During the past two years there have been many experiments reporting the existence of an exotic baryon, the Θ^+.[1,2,3,4] It is observed in the kaon-nucleon system with baryon number one, strangeness plus one, and positively charged (Fig. 1 shows the first claimed observation and Fig. 2 a higher-statistics confirmation). It is, therefore, manifestly exotic composed of five quarks , $ud\,ud\,\bar{s}$. Unfortunately, there are also a large number of experiments that have failed to find this state. In addition, the positive evidence, although relatively numerous, suffers from limited statistics and systematics, although efforts are underway to remedy this situation. A careful examination of older K^+n cross-section data[5], including the charge exchange channel, indicates a total width of at most a few Mev for the Θ^+.[6]

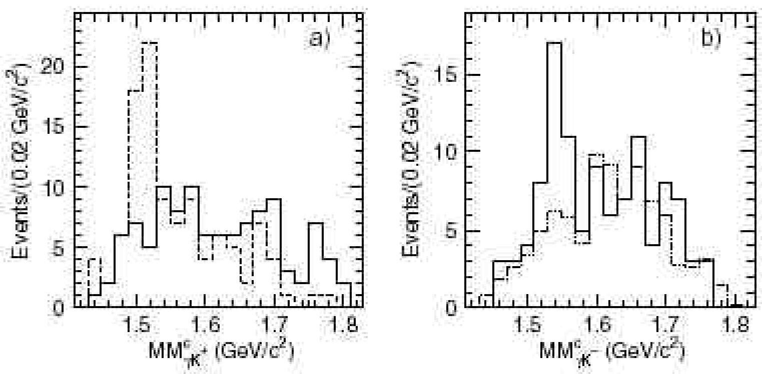

Figure 1 Corrected missing mass recoiling from γK in $\gamma n \rightarrow K^+K^-n$: (a) recoil from γK^+ showing a peak for the $\Lambda^0(1520)$ and (b) recoil from γK^- showing purported Θ^+ signal (from Nakano et al.).

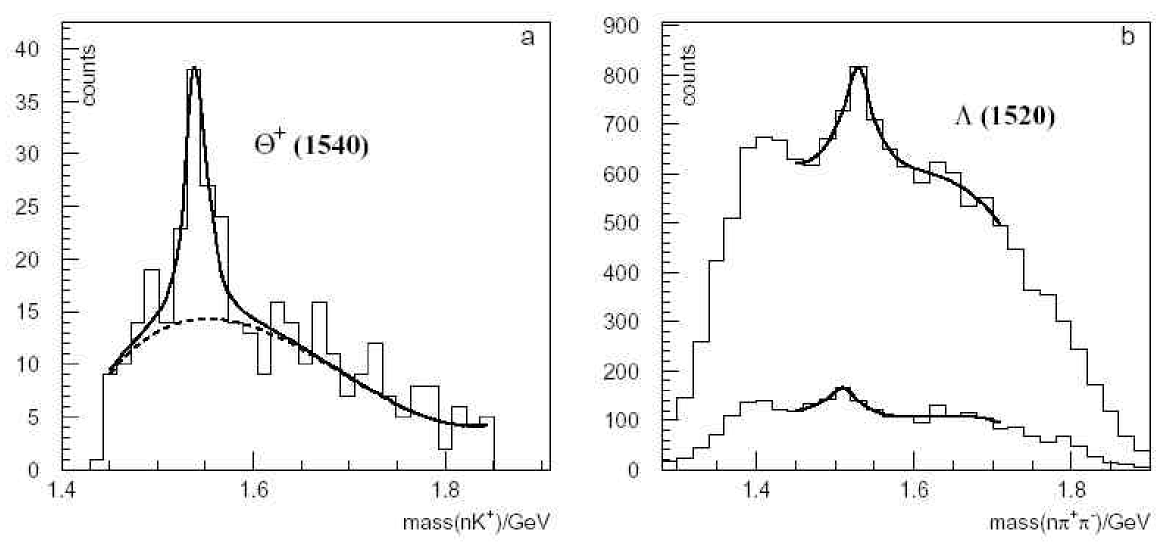

Figure 2 Effective mass spectra in $\gamma p \rightarrow nK_SK^+$ data from the SAPHIR detector at ELSA: (a) the nK^+ mass distribution after cuts and (b) the nK_S mass distribution with and without a cut on the K_S angle.

The possible existence of such exotic states has been the subject of much theoretical speculation[7]. This has involved quark and bag models, and SU(3) chiral soliton models especially the $\overline{10}$ representation. In fact, the mass such an isosinglet member has been predicted to be 1540 Mev, the reported Θ^+ mass. Such an antidecuplet would contain nucleon, sigma and cascade states, the exotic component being a double negative charged cascade, dd ss ū as well as a positively charged cascade, uu ss ū. Although there have been some claims for the observation of these others members of the antidecouplet, the evidence is poor. To say the least, the situation with regard to exotics is murky and in need of clarification. Several searches for the Θ^+ have proven negative. Moreover, as shown in Fig. 3, those experiments which have seen the Θ^+ do not find a consistent value for its mass and there are also problems with the extracted width. Finally, imposing consistency with old but precise measurements of the charge exchange cross-section requires the Θ^+ to have a width of 1-2 MeV. Fig. 4 shows the best of the old measurements along with theoretical estimates of the Θ^+ contribution under various assumptions for the width. The problem of "fitting in" the Θ^+ is compellingly illustrated by the Argand diagrams shown in Fig 5.[8,9] It should be recalled that a resonance, such as the Θ^+, should traverse a complete circle on such a plot.

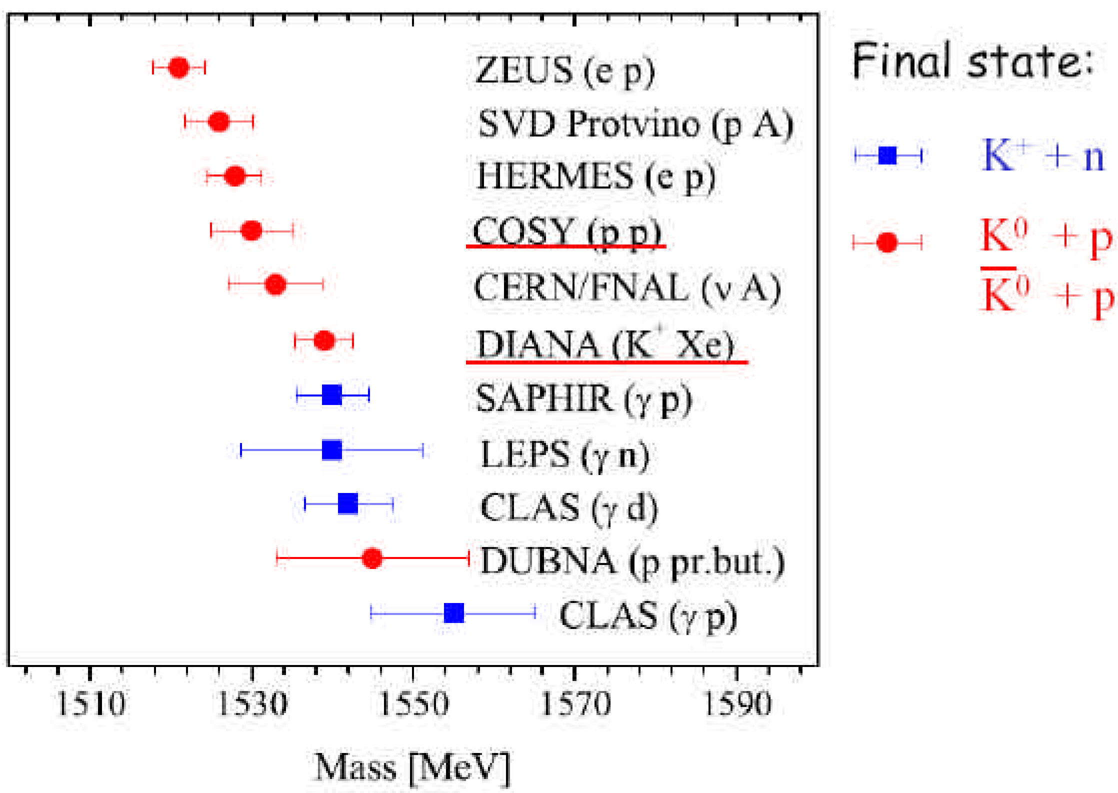

Figure 3 Mass of Θ^+ extracted from various purported observations.

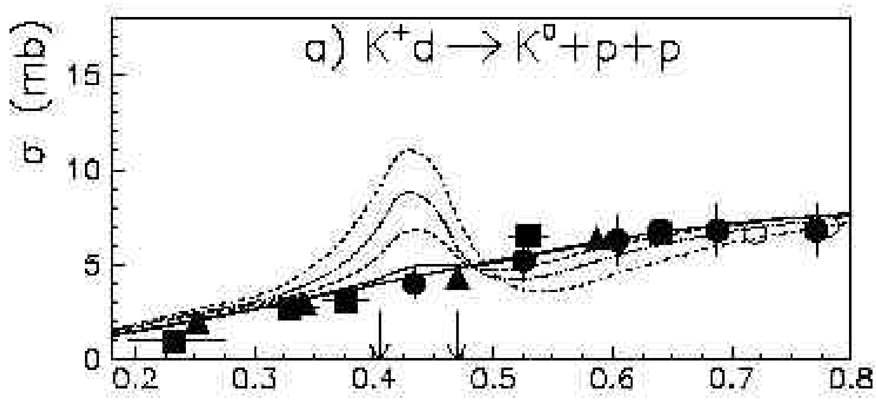

Figure 4 Consistency of previous charge exchange data with the Θ^+ (from A. Sibirtsev et al., hep-ph/0405099).

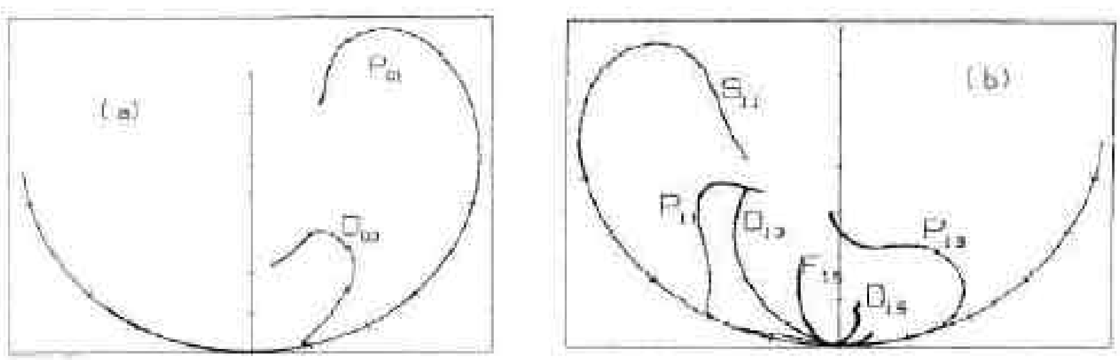

Figure 5 Argand diagrams: (a) Isoscalar partial waves, (b) isovector partial waves. The hash marks are separated by 50 MeV increments in T_{lab}.

The key to resolving the possible existence of any of these types of exotics is the Θ^+. To this end it is proposed to use the existing separated K^+ beam (LESB3) and the K^+ detector (E949) at the AGS to search for the Θ^+ as an S channel resonance. If it exists as proposed, it should be produced with millibarn cross-sections and be readily observable with the available K^+ fluxes, beam and detector at the AGS.

Experimental Concept

It is proposed to produce the Θ^+, if it exists, as an S channel resonance in a formation experiment utilizing a separated K^+ beam. Thus far only one experiment, DIANA[2], claims to have observed the Θ^+ in formation. Fig. 6 shows the K^0p effective mass spectrum from $K^+Xe \rightarrow K^0pXe'$ events in their Xenon bubble chamber. Note that the statistics are rather small and also that the signal is much less significant before the sample is cut to suppress the effects of reinteractions in the Xe nucleus.

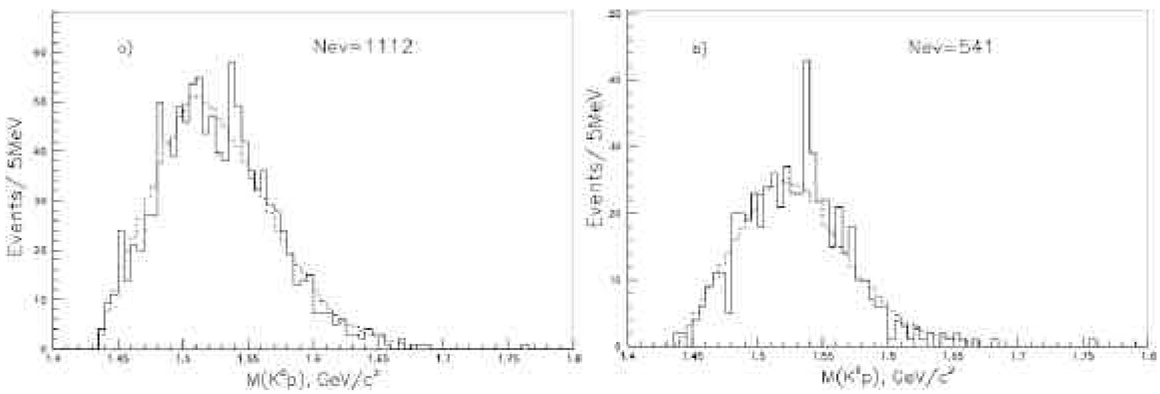

Figure 6 - Effective mass of K^0p from Ref 2. Reaction was $K^+Xe \rightarrow K^0pXe'$. Spectrum (a) for all measured events, (b) for events passing additional cuts aimed at suppressing K^0 and proton reinteractions in nuclear matter.

In the experiment being considered here, the statistics would be enormously enhanced over those of Ref 2, and the nuclear medium would be much smaller (C instead of Xe). The reaction is:

$$K^+n \rightarrow \Theta^+ \rightarrow K^0p \text{ with } K^0 \rightarrow \pi^+\pi^- \qquad (1)$$

where the neutrons are supplied by the carbon in the E949 scintillator target.

In essence, the K^+ meson loses energy in the target (acting in the accustomed manner) until its energy matches that of the Θ^+ resonance whereupon there is an excess of events in reaction (1) and a consequent reduction, as the K^+ energy becomes lower and is again non-resonant. The preferred manner to measure this reaction is to observe both the final state proton and the two-pion decay of the K^0 and to examine the effective mass of these particles. If the Θ^+ exists, one should see an excess of such events at the Θ^+ mass. This distribution should be unaffected by the Fermi motion but sensitive to rescattering in the target and the acceptance and detection efficiency of the detector. A second and complimentary method consists of observing the pions from the K^0 decay and measuring this production rate as a function of position in the target. Again, one should see an increase in the yield as the K^+ loses energy in the target and at some point encounters the Θ^+ resonance. This distribution is, however, affected by the Fermi motion of the struck neutron in the target, the precision of the incoming K^+ momentum, and any straggling in the target as well as the aforementioned detector efficiencies. The uncertainties introduced by the Fermi motion can be partially ameliorated via the missing mass technique successfully implemented in the photoproduction studies by Nakano et al[1].

The effectiveness of these techniques can be ascertained by running a K^- beam into the same target and apparatus and studying the well established $\Lambda(1520)$ resonance which has a similar mass and decay modes, but opposite strangeness to the Θ^+. In this instance, the reaction is

$$K^- p \to \Lambda^0(1520) \to \overline{K}^0 n \text{ with } \overline{K}^0 \to \pi^+\pi^- \quad (2)$$

very analogous to reaction (1) and

$$\Lambda^0(1520) \to \Sigma^0\pi^0 \text{ with } \Sigma^0 \to \gamma\Lambda \quad (3)$$
$$\Lambda^0(1520) \to \Lambda\pi^+\pi^- \quad (4)$$

One utilizes the effective mass technique for the Λ(1520) in reaction (3) and (4) since one will observe and, measures all the particles from its decay. One can then compare the properties of this resonance, mass width, with the accepted values. By again just measuring the pions from K^o decay, reaction (2) and investigating the distribution of the position of the K^o decays along the target length, one can look for an excess of events due to the S channel production of this Λ^o resonance. One should see it if this technique works and thus be able to determine the effects of the Fermi motion. This is slightly different from (1) in that the proton can be either in the carbon nucleus or exist as free hydrogen. Again the missing mass technique should aid in unraveling the effects of Fermi motion especially since in this case one knows the answer.

How either of these methods succeeds or fails depends on the details that we will address in the next sections.

Beam and Target

This experiment will utilize the existing low energy separated beam III (LESB III)[10] at the AGS. This has successfully been run for several years, most recently yielding 13.5×10^6 710 MeV/c K^+ per spill with 4.5×10^{13} protons on target. A preferred mode of running this experiment would be parasitically with the polarized proton program at RHIC. In this case the AGS can deliver 10^{12} protons per pulse to the C target and, therefore, 3×10^5 K^+'s per pulse. Scaling to 475 MeV/c this implies $F_K = 2.8 \times 10^4$ K^+'s, which as will be shown later to be more than adequate for the experiment. The polarity of the separated beam can be easily changed so that one can also run separated K^- beams into the same scintillation target detector. The K^- flux is expected to be a factor of 5 less than the K^+ although it has not been experimentally verified.

The target consists of 413 5-mm square plastic scintillating fibers of 310 cm length. The scintillator is PVT with a density of 1.032 gm/cm^3 and a hydrogen to carbon ratio of ~1.1:1. Impacted by an incoming kaon of momentum 475 Mev/c, the active fiducial length of target of 25 cm will span a mass region for the Θ^+ from 1550-1520 Mev, encompassing the reported values for the Θ^+ mass. The yield of events per millibarn per 25 cm of target per pulse is therefore

$$Y = \rho l \sigma N_A F_K f_n$$
$$= 1.032 \times 25 \times 10^{-27} \times 6.022 \; 10^{23} \times 2.8 \; 10^4 \times 6/13.1 = 200/\text{mb/pulse} \quad (5)$$

where the last factor is the fraction of neutrons in the scintillator target.

Detector

This experiment will use the existing E949 detector , which is positioned on the LESB III line at the AGS. This detector has been used for the very successful E787 experiment, which found two examples of the very rare $K^+ \rightarrow \pi\nu\nu$ decay[11], and made many other measurements of rare decays of the K^+. It was upgraded into the present E949 detector 4 years ago, and the initial run has yielded another example of this very rare decay mode[12]. The E949 collaboration has been awaiting funding to continue measurements.

The detector has been described in several publications[13]. Incoming kaons are identified with a lucite Cerenkov counter, degraded to ~300 MeV/c, and observed in a hodoscope of two planes of scintillator, with 16 elements/plane, located just upstream of the scintillating fiber target discussed previously. In this proposed experiment, the degrader would be removed, and the Cerenkov would be used to veto beam pions. Charged products emerging from the target are detected in a cylindrical wire chamber and a Range Stack of 24 azimuthally symmetric sectors each consisting of 18 layers of 2-cm thick, 1.8 m long scintillation counters. Thin counters surrounding the drift chamber define the fiducial area of the detector. The elements that measure the charged decay products are surrounded by CsI and Pb-scintillator detectors in which photons are converted and detected. The active elements are contained within a cylindrical magnet, typically set at 1-Tesla. The energy-loss and time of each particle is recorded in each scintillator with a series of ADCs, TDCs, and devices that record the pulse shape in each counter in 2-ns intervals. Schematic end and side views of the detector are shown in Fig 6.

A trigger sensitive to charge-exchange events was created and tested in this detector in 1997, and was used to provide data for a thesis experiment “Low Energy (K^+,^{12}C) Charge Exchange Cross Section Measurements”[14]. A typical charge-exchange event is shown in Fig 7. The K^0 mass resolution observed was ~5 MeV rms as seen in Fig 8. The acceptance of the target/trigger counter combination for charge exchange events is shown in Fig 9.

The detector has been left in position since the conclusion of the 2002 E949 run. A cosmic-ray test run will be conducted during August 2004, and should confirm that the detector will be ready to take data for this measurement when approved.

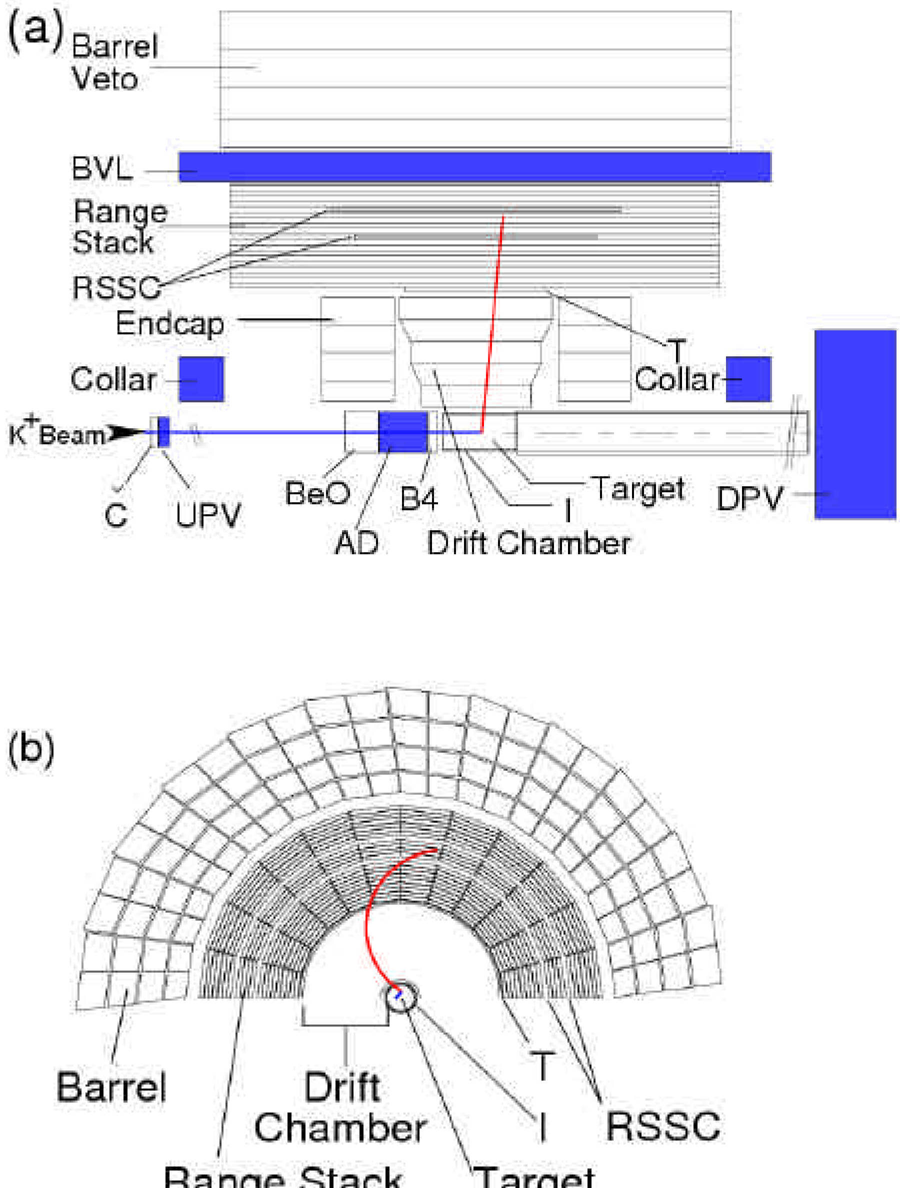

Figure 7 (a) Side and (b) end view of upper half of E949 detector

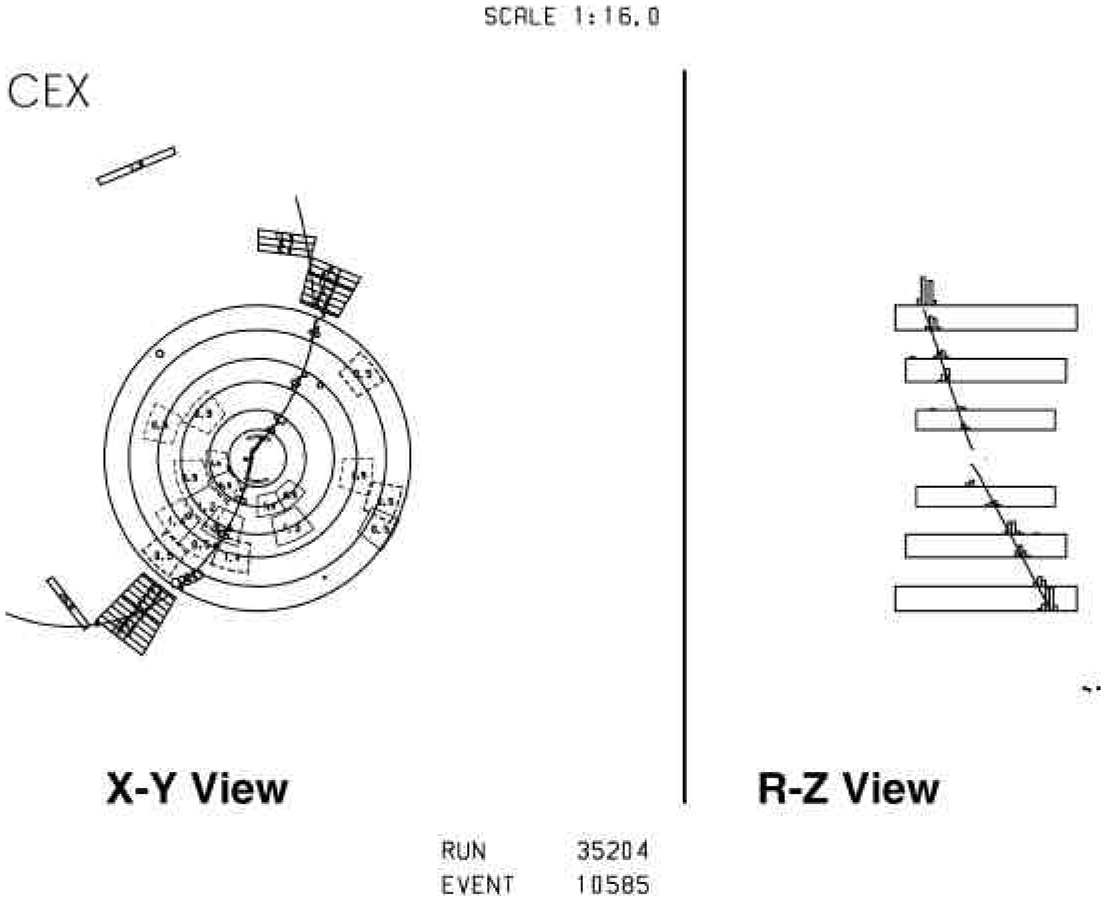

Figure 8 End and side view of charge exchange event in E787

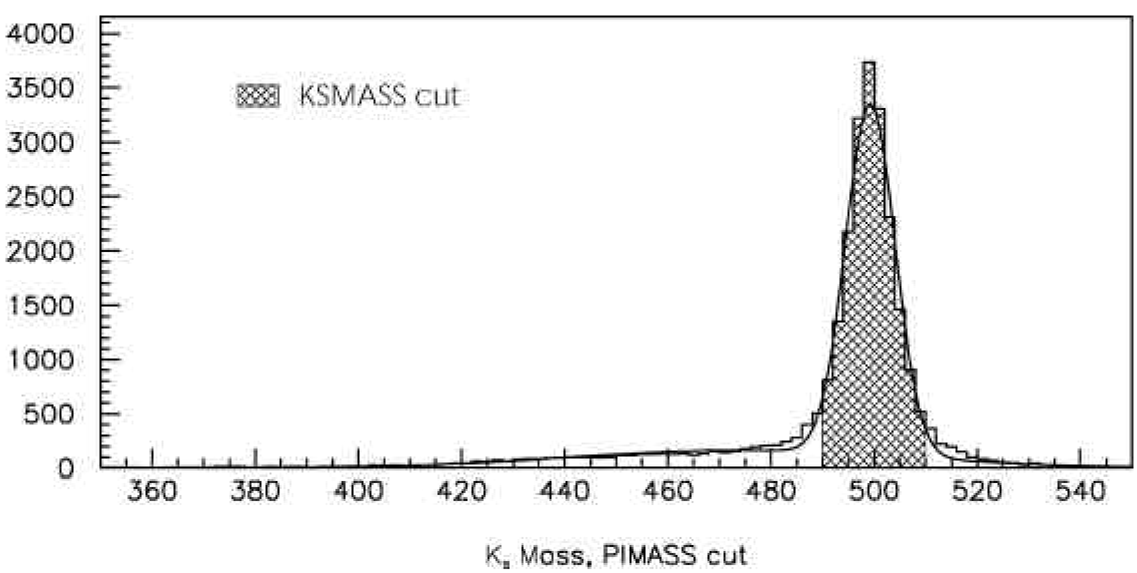

Figure 9 pi-pi effective mass from Ng thesis

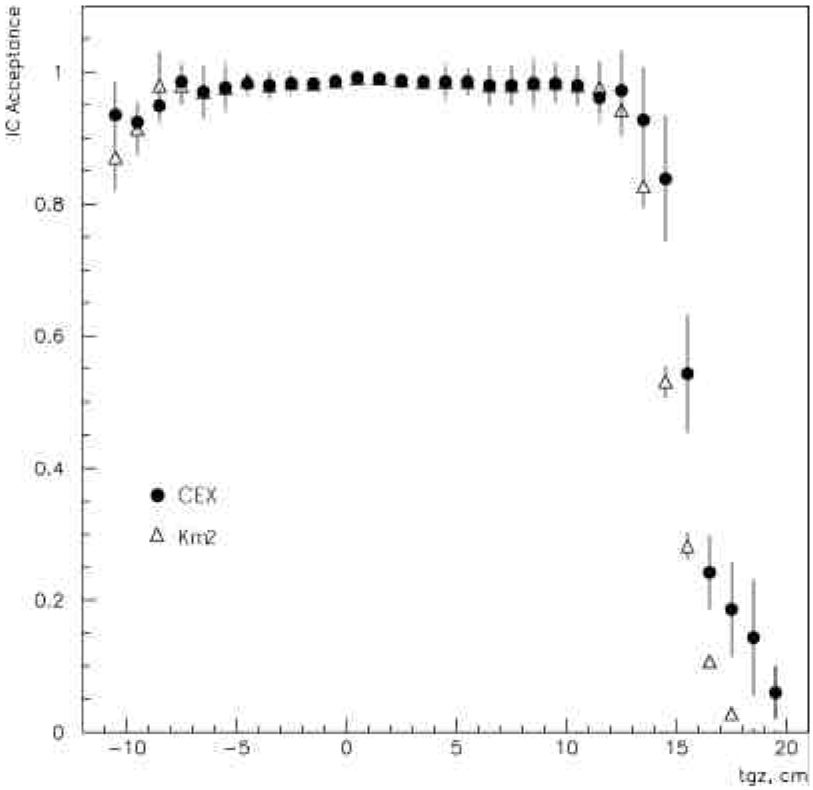

Figure 10 Acceptance of E787 target and trigger counters for charge exchange and $K^+ \rightarrow \mu^+ \nu$ events.

Expected Yields

The expected cross section for the Θ^+ can be estimated from the resonant Breit Wigner expression

$$\sigma_{BW}(E) = (2J+1)/((2S_1+1)\,(2S_2+1)) \quad \pi/k^2 \;\; B_{in}\, B_{out} \;\; \Gamma^2/((E-M)^2+\Gamma^2/4) \qquad (6)$$

Where k is the c of m momentum. S_1, S_2 incident spins, Γ width of the resonance, B_{in}, B_{out}, branching ratios into initial and final channels with $J=1/2$, $S_1=0$, $S_2=1/2$, $B_{in}= B_{out}=1/2$.

This reduces to

$$\sigma_{BW}(E) = \pi/4k^2 \;\; \Gamma^2/((E-M)^2+\Gamma^2/4) \qquad (7)$$

At resonance E=M, therefore

$$\sigma_{BW} = \pi/k^2 = 16.8 \text{ mb} \qquad (8)$$

The integrated cross section

$$\int \sigma dE = \pi/2k^2 \;\; \Gamma = 26.4 \text{ mb-MeV} \qquad (9)$$

And for a width of Γ= 1 Mev which is the present estimate[159], this gives a value of 26.4 mb.

The charge exchange cross section (1) has been measured in the incoming K^+ momentum range of 200-700 Mev/c to smoothly rising as is evident in Fig. 4. At 475 MeV/c it is 4 mb with no evidence for any resonant formation. Therefore, one should plan on the production of 4 mb x 200 events/mb/pulse = 800 events/pulse over the whole target for the charge exchange cross section. If the Θ^+ exists there should be an excess of events of at least an equal magnitude.

The situation for observing the Λ(1520) appears also to be quite favorable. The cross section for its production with K^- is of the order of 100 mb! Its width has been accurately measured to be $\Gamma = 15.6 \pm 1.0$ Mev and the major branching ratios are

$$\begin{array}{l} 45\%\ N\bar{K} \text{ of which } \tfrac{1}{2} \text{is } \bar{K}^0 n \text{ and } \tfrac{1}{2}\text{is } K^- p \\ 42\%\ \Sigma\pi \text{ of which } 1/3 \text{ is } \Sigma^0\pi^0,\ 1/3\ \Sigma^-\pi^+, \text{ and } 1/3\ \Sigma^+\pi^- \\ 10\%\ \Lambda\pi\pi \text{ of which } \tfrac{1}{2} \text{ is } \Lambda\pi^+\pi^- \end{array} \qquad (10)$$

The present strategy is to utilize the $\Sigma^0\pi^0$ channel, where one observes the Λ^0 and gamma rays (and probably the $\Lambda\pi^+\pi^-$ channel) in investigating the effectiveness of observing the Λ^o(1520) in the effective mass distribution of the observed particles. As noted earlier, this is independent of the Fermi momentum of the struck proton. We would also look in the $\bar{K}^0 n$ channel as mentioned above.

<u>Present and Future Studies and Monte Carlo's</u>

There are presently two independent 4-vector level Monte Carlo programs under development. These will be used to calculate the acceptance of the E949 detector for this reaction and allow optimization of the experiment. If they indicate that the proposed experiment is viable, the detailed E949 Monte Carlo, UMC, will be adapted to the current use. In addition a number of studies are underway using data collected by E949 in 2002. These include a study of $\pi^+ p$ elastic scattering events (to determine the effectiveness of the E949 target in measuring the proton kinematics) and a study of $K^+ \to K^0$ charge exchange events.

<u>Discussion</u>

It is evident that if the Θ^+ exists it should be strongly coupled to the kaon nucleon system. As such it seems prudent to search for this resonant state with K^+'s and neutrons. It is fortuitous that such a beam, target, detector and analysis system all exist at

Experiment 949 at the AGS. The expected cross section for both the Θ^+ and the Λ (1520) calibrations are very large 25-100 mbarns. The rates will therefore also be very large. As noted earlier there are a variety of search techniques that will be utilized. The pacing reaction will involve seeing both the K^o decay and the proton from the Θ^+. The requested running time will ensure a sufficient accumulation of such events, after all cuts are made. The aim is to clearly observe the Θ^+ if it exists and, if not, to set a meaningful limit on its properties.

Request

We believe that this proposed experiment is one of the most definitive ways to resolve the important question of the existence of the Θ^+ pentaquark. The demand on resources to execute this search is minimal, the largest expenditure being for the power for running the AGS, beam lines, and detector. In the next few months, detailed studies of acceptance, and detection efficiency of observing the pertinent channels as well as evaluating sensitivities and systematic parameters will be executed. If these prove positive, as expected, a detailed proposal will quickly follow. From the preliminary estimates we expect that the execution of this experiment will require hundreds of hours of AGS running time, to be accomplished parasitically with polarized proton running at RHIC. We request affirmation of the physics goals of this letter of intent, encouragement to develop such a full scale proposal and the setting up of procedural mechanisms so that if all proves successful this experiment can be implemented on a rapid time scale.

References

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