EXOTIC STATE SEARCHES AT THE SPRING-8: OBSERVATION OF A PENTAQUARK STATE Θ^+ BARYON[†]

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Abstract

A narrow resonance peak was observed at 1.54 ± 0.01 GeV/c^2 as an exotic baryon with strangeness $S = +1$ in the $\gamma + n \to K^+ + K^- + n$ reaction on ^{12}C. The new state have a width smaller than 0.025 GeV/c^2 and a Gaussian significance of 4.6σ. It can not be interpreted as three quark state and is consistent with the lightest member of an antidecuplet of baryons predicted by the chiral soliton model.

INTRODUCTION

The constituent quark model has been remarkably successful to describe most of the experimentally observed mesons and baryons. Beyond conventional hadrons, exotic states such as glueballs, hybrid mesons, and other multi-quark states are not prohibited in QCD. There is a different approach by the Skyrme model [1] that is originated in the same QCD. In this direction, following the pioneering works [2, 3], Diakonov, Petrov and Polyakov (DPP) proposed a possible existence of the $S = +1$ $J^P = 1/2^+$ resonance at 1.53 GeV/c^2 with a width less than 0.015 GeV/c^2 using the chiral soliton model [4]. The Θ^+ (originally denoted the Z^+) is the lightest member of the anti-decuplet which appears as the third rotational excitation states. Their model simply assumes the relatively well established nucleon resonance $N(1710, 1/2^+)$ as a nucleon-like member of the anti-decuplet. The mass formula for the members of the antidecuplet is proposed as

$$M = [1.89 - Y \times 0.18\ ]\ GeV/c^2 \qquad (1)$$

where Y is a hypercharge.

Motivated by the resonance-like structure appeared around K^+ momentum of 1 GeV/c in both K^+p and K^+n total cross-sections, experimental studies on the K^+N reactions started from 1960's. It is to be noted that most of the searches were performed in the mass range between 1.74 and 2.16 GeV/c^2. Although the possible Z^* baryon resonances were reviewed in the 1986 baryon listings by the PDG [5], evidence of their existence was concluded as poor.

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One of our experimental goal is to search various kinds of exotic states through photonuclear reactions. The present experiment was motivated in part by the DPP prediction mentioned above, and the experimental result was published in the article [6]. We describe this paper including some issues that were not mentioned at the workshop or appeared afterward.

EXPERIMENTAL METHOD

The experiment was carried out at the Laser-Electron Photon facility at the SPring-8 (LEPS) [7]. Photon beam is produced by Compton scattering of laser photons on the circulating 8 GeV electrons and beam energy is tagged by analyzing scattered electron momentum. The maximum photon energy is determined by the wave length of the laser, and it is 2.4 GeV when a 351 nm Ar laser is used.

Energy spectrum of a photon beam is relatively flat as shown in Fig. 1 and photons are highly polarized when laser photons are polarized. Un-collimated beam size in standard deviation(σ) is 3 mm vertcally and 8 mm horizontally at the target position about 70 m downstream of the Compton scattering region. Typical tagged photon flux above 1.5 GeV was $\sim 1 \times 10^6$ per second.

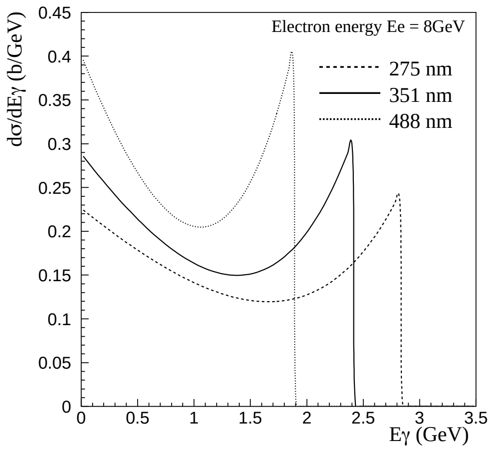

Figure 1. Energy spectrum of a Laser-Electron Photon beam.

Experimental setup was designed for the study of ϕ meson production from protons. Photons hit a liquid hydrogen target (LH_2) of 5 cm thick after passing through a charged particle veto counter (VC). The LEPS detector consisted of a start trigger counter (SC), a silica aerogel Čerenkov counter (AC), a silicon-strip vertex detector (SSD), an upstream drift chamber, a 0.7T dipole magnet, two sets of downstream drift chambers, and a time-of-flight scintillator array(TOF) as shown in Fig. 2. The detector acceptance covered forward angle of ± 0.4 and ± 0.2 rad in the horizontal and vertical directions, respectively. Typical detector resolutions in σ for tagged E_γ, momentum, time-of-flight, and

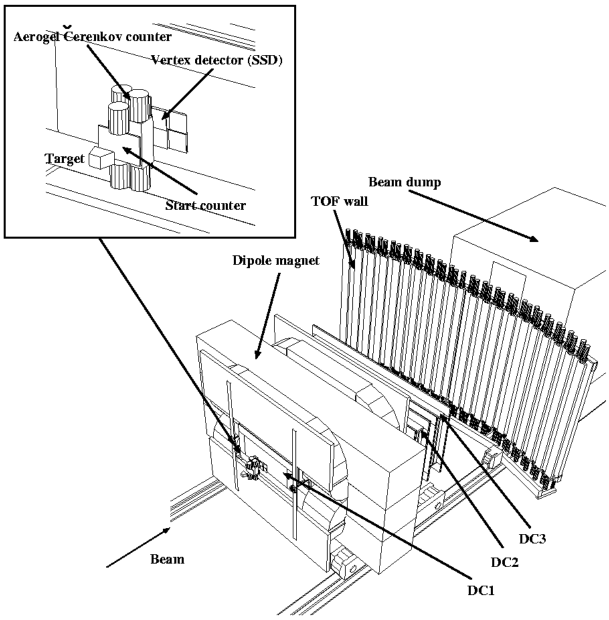

Figure 2. The LEPS detector setup.

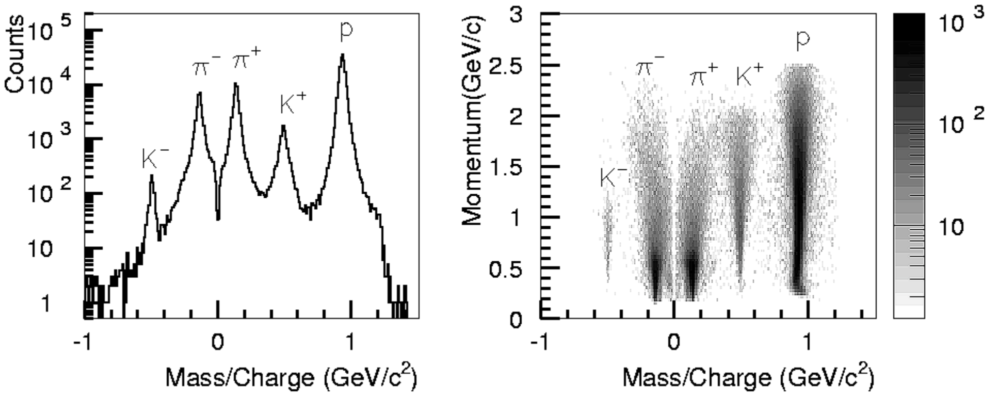

Figure 3: The Mass distribution.

mass (momentum dependent) were 0.015 GeV/c^2, 0.006 GeV/c at 1 GeV/c, 150 $p$sec for a flight length of $\sim$ 4 m from the target to the TOF, and 0.01 GeV/c^2 for 1 GeV/c kaon, respectively. Particle identification was applied within 3 σ in this analysis, and its effectiveness can be viewed in the mass spectrum in Fig. 3.

e^+e^- pairs produced in the very forward angles were blocked by horizontal lead bars which were set in the median plane inside the magnet gap. The trigger simply required a hadron event by applying a tagging counter hit, no charged particle before the target, charged particles after the target, no signal in the AC, and at least one hit on the TOF wall. AC fires for electrons and positrons, and for pions with momentum higher than 0.6 GeV/c by the choice of a refractive index of 1.03. A typical trigger rate was about 20 events per second. The data taking was carried out during December, 2000 to June, 2001.

DATA ANALYSIS

From the total amount of 4.3×10^7 triggers, 8.0×10^3 events with a K^+K^- pair were reconstructed. Data reduction was carried out in the following scheme.

(1) Vertex position cut

The SC, which was used as a neutron target for the search of Θ^+, was a 0.5 cm thick plastic scintillator (polystyrene) and was placed at 9.5 cm downstream of LH_2. K^+K^- pair events from the SC were identified by selecting vertex position along beam direction. Events that originate from a reaction in the SC were clearly seen in Fig. 4. Events from maximum photon energy region above 2.35 GeV were omitted in consideration of increasing background contribution to the signal with increasing energy. These cuts reduced the data sample to $3.2 \times 10^3 K^+K^-$ events.

(2) Missing mass cut

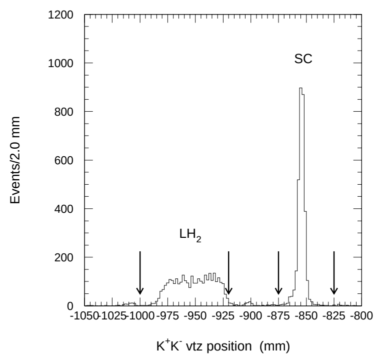

Figure 4. Vertex position for K^+K^- events along the photon beam direction. Arrows indicate the cut position for SC or LH_2 events. SC events were used for exotic state search.

In the reaction $\gamma N \rightarrow K^+K^-X$, M_X was required to be nucleon and the rest of carbon nucleus be spectator. The missing mass $MM_{\gamma K^+K^-}$ in the above reaction was calculated by assuming a qusi-free γN scattering. A total of 1.8×10^3 events survived after applying $0.90 < MM_{\gamma K^+K^-} < 0.98$ GeV/c^2.

(3) ϕ meson cut

Most of the remaining K^+K^- events (85%), which were from ϕ meson photoproduction and were uninteresting events in this report, were cut by applying $1.00 < M(K^+K^-) < 1.04$ GeV/c^2 as in Fig. 5.

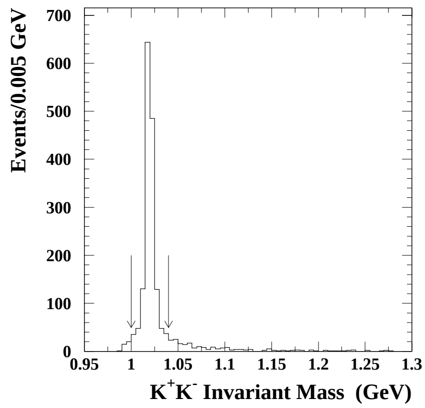

Figure 5. Invariant K^+K^- mass distributions for the SC events. ϕ meson contributions were cut for exotic state search as indicated by arrows.

(4) Proton cut

K^+K^- events, of which reactions were originated from protons, were eliminated by requiring SSD hit. The direction and momentum of the nucleon in the final state was calculated from the K^+ and K^- momenta. Events were rejected if the recoiled nucleon was out of the SSD acceptance or was the momentum smaller than 0.35 GeV/c since an uncertainty in the calculation becomes large for low momentum case. 108 events were eliminated by requiring that the hit position in the SSD agreed with the expected hit position within 45 mm. This distance was chosen to take the Fermi motion in ^{12}C into account. A total of 109 events satisfied all the selection criteria ("signal sample").

A raw missing mass calculation done above was obtained without considering the Fermi motion in ^{12}C. To evaluate this effect, well known process $\gamma n \rightarrow K^+\Sigma^- \rightarrow K^+\pi^-n$ was studied. Clear correlations are seen in the missing mass plots Fig. 6, where $MM_{\gamma K^+}$ and $MM_{\gamma K^+\pi^-}$ were obtained for the $\gamma N \rightarrow K^+X$ and $\gamma N \rightarrow K^+\pi^-N$ channels by assuming the nucleons at rest. This is understood by the fact that the nucleons in the two channels are identical. Considering the above missing mass correlation and setting the nucleon mass to M_N, the Fermi motion corrected missing mass $MM^c_{\gamma K^+}$ is obtained as

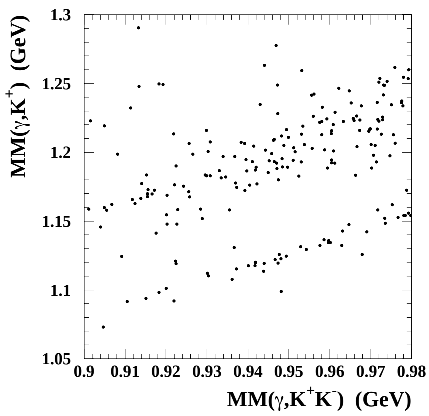

Figure 6. The scatter plot of $MM_{\gamma K^+}$ *vs.* $MM_{\gamma K^+\pi^-}$ for $K^+\pi^-$ photoproductions in the SC.

$$MM^c_{\gamma K^+} = MM_{\gamma K^+} - MM_{\gamma K^+\pi^-} + M_N. \quad (2)$$

Eq. (2) compensates not only the Fermi motion but also the experimental resolutions and the binding energy of the nucleon in ^{12}C. The Fermi motion effect is the major contribution in the analysis. Although there is only a smeared distribution in the raw $MM_{\gamma K^+}$ (dashed line in Fig.7), the Λ and the Σ^- peaks are separated after the correction (solid line in Fig.7). Note that this correction is not a good approximation for events with $MM_{\gamma K^+\pi^-}$ far from the nucleon rest mass, and is good in case of a decay with a small Q value. The

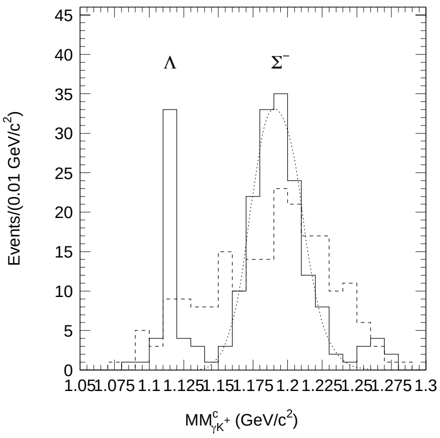

Figure 7: The corrected missing mass distribution $MM^c_{\gamma K^+}$ [Eq.(2)] for the $K^+\pi^-$ events from the SC (solid line) and for Monte Carlo events for the $\gamma n \to K^+\Sigma^-$ channel (dotted curve). The dashed line shows the missing mass distribution $MM_{\gamma K^+}$ which was obtained from the projection of the events in Fig. 6 on to the vertical axis without the Fermi-motion correction.

latter effect is seen in the small width for the Λ and the large width for the Σ^- because of the imperfection of the correction due to a large Q value for the Σ^-.

The corrected missing mass $MM^c_{\gamma K^\pm}$ for K^+K^- events is given as

$$MM^c_{\gamma K^\pm} = MM_{\gamma K^\pm} - MM_{\gamma K^+K^-} + M_N. \tag{3}$$

Fig. 8 shows no obvious peaks in a $MM^c_{\gamma K^+}$ distribution of the signal sample (109 events) that satisfied all the selection criteria (dotted line), and shows a clear peak due to the $\gamma p \to K^+\Lambda(1520) \to K^+K^-p$ process in the 108 events that agreed the proton hit in the SSD (solid line). Effectiveness of a proton cut is verified that the $\Lambda(1520)$ peak does not show up in the dotted line plot.

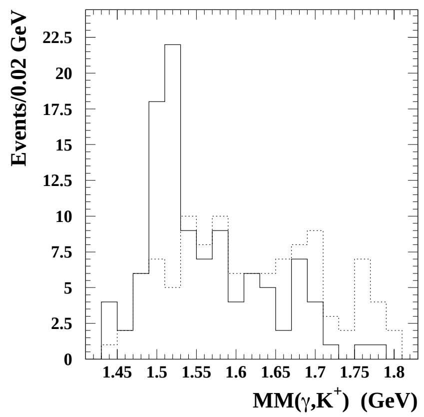

Figure 8: The corrected missing mass distribution $MM^c_{\gamma K^+}$ [Eq.(3)] for the K^+K^- productions for the signal sample (dotted line) and for events from the SC with a proton hit in the SSD (solid line).

Fig. 9 shows the $MM^c_{\gamma K^-}$ distribution of the signal sample. A prominent peak at 1.54 GeV/c^2 is observed with 36 events in the peak region between 1.51 and 1.57 GeV/c^2. To estimate the background due to the non-resonant K^+K^- production in the peak region defined above, the missing mass distribution of the signal sample in the region above 1.59 GeV/c^2 was fitted by a distribution of events from the LH_2. LH_2 sample required the same selection criteria except for the shifted vtz window and a proton hit in the SSD. Since the $\Lambda(1520)$ contribution was removed from the signal sample, it was removed from LH_2 sample for $1.51 \leq MM^c_{\gamma K^+} < 1.53$ GeV/c^2. The best fit with a χ^2 of 7.2 for 8 degrees of freedom is obtained with a scale factor of 0.2 as shown with a dotted line in Fig. 9. Resulting background level in the peak region is estimated to be $17.0 \pm 2.2 \pm 1.8$, where the first uncertainty is the error in the fitting in the region above 1.59 GeV/c^2 and the second is a statistical uncertainty in the peak region. The combined uncertainty of the background level is ± 2.8. The estimated number of the signal events after subtracting background is 19.0 ± 2.8, which corresponds to a Gaussian significance of $4.6^{+1.2}_{-1.0}\sigma$ $(19.0/\sqrt{17.0})$. The signal region between 1.47 and 1.61 GeV/c^2 after background subtraction was compared with Monte Carlo simulations assuming a Breit-Wigner function for a resonance shape. The best fit was 1.54 ± 0.01 (statistical) GeV/c^2. The systematic error was speculated to 0.005 GeV/c^2 by referring the known particle Σ^-, of which peak position was 0.005 GeV/c^2 smaller than the PDG value of 1.197 GeV/c^2. The width Γ of the resonance cannot be determined by the fitting since the zero width gives the minimum χ^2 of 1.6 for 4 degrees of freedom. The upper limit for the width was determined to be 0.025 GeV/c^2 with a confidence level of 90%.

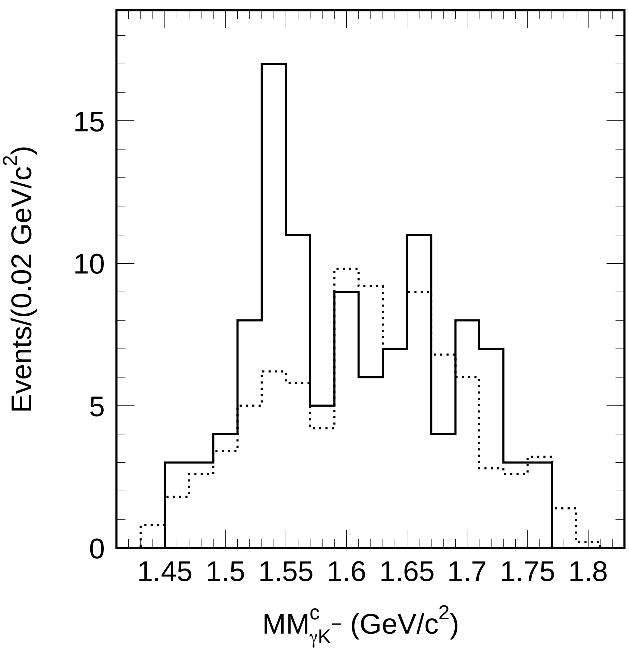

Figure 9: The corrected missing mass distribution $MM^c_{\gamma K^-}$ [Eq.(3)] for the signal sample (solid line) and for events from the LH_2 (dotted line) normalized by a hit in the region above 1.59 GeV/c^2.

To make sure that the observed peak is not due to a fake one, the mass cut on one of the kaons was tightened from 3 σ to 2 σ, and also the kaon mass was intentionally assigned for the pions in the missing mass calculations. The peak was not affected in both cases, and it was also confirmed that the peak is not due to the effect of the tails of the ϕ mesons.

DISCUSSION

After we announced the evidence of Θ^+, significant deal of activities have been reported in both experimental and theoretical fields. Because of the peculiar nature and relatively small statistical significance of the new state, experimental confirmation was seriously awaited. Several experimental results appeared in succession from the DIANA collaboration at the ITEP [8], CLAS collaboration at the JLab [9], SAPHIR collaboration at the ELSA [10], and a neutrino experiment [11]. In all cases the mass is near 1.54 GeV/c^2 and the width is smaller than 0.025 GeV/c^2. There are informal announces of again consistent observations of Θ^+ from HERMES and ZEUS. It is instructive that the DIANA collaboration reanalyzed almost 15 years old data which was obtained in the direct s-channel K^+N measurements with X_e bubble chamber.

The most surprising point was the narrowness of the Θ^+ width which is claimed to be smaller than 0.009 GeV/c^2 [8]. Recent partial wave analysis on K^+N elastic scattering by Arndt, Strakovsky and Workman indicated that the width of Θ^+ is likely smaller than 0.001 GeV/c^2 [12]. One of the speculation required Θ^+ to be isotensor, and the isospin violating decay causes the narrow width [13]. This explanation seems unlike if isospin of Θ^+ is confirmed to be zero [10, 14].

In fact we only know the Θ^+ mass but not other quantum numbers. Spin and parity of Θ^+ can be determined in principle by measuring the decay angular distribution and nucleon polarization as in the textbooks. This is extremely difficult to do experimentally in straightforward way. To determine quantum numbers is our crucial task now on [15, 16, 17].

It is natural to ask whether Θ^+ is a resonance or a baryon-meson molecular like state. It seems unusual to assume Θ^+ to be a baryon-meson molecular state because of its narrow width according to Jaffe and Wilczek (JW) [18].

A discovery of the Θ^+ was certainly guided by the prediction based on the chiral soliton model by DPP. On the other hand quark model approaches have been reported recently with highly correlated diquak-diquark [18] and diquark-triquark [19] schemes. If Θ^+ mass is set to experimentally measured value of 1.54 GeV/c^2 in each model, expected exotic Ξ mass is quite different between correlated quark model and chiral soliton model predictions. Exotic Ξ mass is at 1.75 GeV/c^2 by a quark model of JW, although it is at 2.07 GeV/c^2 from eq.(1) with S = -2 by a chiral soliton model by DDP. DDP predicts the width to be greater than 0.14 GeV/c^2 in addition. Recently reported observation of exotic Ξ by NA49 collaboration indicates that the mass is at 1.862 GeV/c^2 with a width narrower than 0.018 GeV/c^2 [20]. The measured mass does not fit in any predictions, and Diakonov and Petrov proposes a revised model [21]. There have been significant discoveries recently in meson spectroscopy field from the B-collider experiments. Unusually narrow meson states were observed in the BABAR, BELLE and other detectors [22]. These states may be attributed to exotic tetraquark states. Further researches on the Θ^+ and exotic Ξ baryons together with the exotic mesons will boost in understanding the nature of the exotic states.

CONCLUSION

The LEPS measurement provides the first evidence for the existence of a S = +1 narrow baryon resonance at 1.54 ± 0.01 GeV/c^2 in the K^- missing mass spectrum of the $\gamma n \to K^+K^-n$ reaction on ^{12}C. The Gaussian significance is estimated to be 4.6 σ and the width is smaller than 0.025 GeV/c^2. The result is surprisingly coincided with the DPP's prediction. This state is certainly an exotic baryon with a quark configuration of $uudd\bar{s}$.

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