5-QUARK BARYON Θ^+ AND RELATED TOPICS of SPring-8*

H. Kohri

For the LEPS Collaboration

RCNP, Osaka University, Ibaraki, Osaka 567-0047, Japan

(Received February 10, 2004)

5-quark baryon Θ^+ with $S = +1$ was discovered in photoproduction from the neutron in ^{12}C at LEPS of SPring-8. A Gaussian significance was 4.6σ. The mass and width of the Θ^+ were 1.54 ± 0.01 GeV/c^2 and smaller than 25 MeV/c^2, respectively. Recent results from other experiments confirmed the existence of the Θ^+. The Θ^+ can be interpreted as a molecular meson–baryon resonance or alternatively as an exotic five quark state ($uudd\bar{s}$). Photon beam asymmetries for the $p(\gamma,\ K^+)\Lambda$ and $p(\gamma,\ K^+)\Sigma^0$ reactions were measured at $E_\gamma = 1.5$–2.4 GeV and $0.6 < \cos(\theta^{\mathrm{c.m.}}_{K^+}) < 1.0$ by using linearly polarized photon beam. The measured asymmetries are positive and gradually increase with rising photon energy. There is no theoretical prediction which perfectly reproduces the measurements. Including the new results in the development of theoretical models is crucial for understanding the reaction mechanism and to test the presence of missing resonances.

PACS numbers: 13.60.Le, 13.60.Rj, 14.20.Jn

1. Introduction

$S = +1$ baryon searches were extensively carried out in kaon–nucleon (KN) scatterings with partial-wave analyses. In 1986 there were some candidates, such as $Z_0(1780)$ and $Z_0(1865)$ [1]. Later the summary of the $S = +1$ baryon resonances was dropped from the Particle Data Group listings because the evidence of the existence was poor.

Diakonov, Petrov, and Polyakov predicted a new particle, Z^+(renamed as Θ^+ later) with a relatively low mass of about 1.53 GeV/c^2 and a total width of 15 MeV/c^2 with the chiral soliton model [2]. They assumed an

* Presented at the XXVIII Mazurian Lakes School of Physics, Krzyże, Poland, August 31–September 7, 2003.

anti-decuplet and $N(1710)$ was used to anchor the anti-decuplet for predicting masses. Most of past searches for $S = +1$ baryons in KN scatterings were done in higher mass region than 1.53 GeV/c^2. This prediction in part motivated a search for the Θ^+, which was predicted to decay to K^+n or K^0p, at LEPS. The photon beam was a good tool to search for the Θ^+ by detecting K^-K^+ for the reaction $\gamma n \to K^-\Theta^+ \to K^-K^+n$.

2. Experiment

The LEPS experiment facility was constructed at SPring-8 in Japan to mainly study the ϕ meson photoproduction at the near threshold region at forward angles. Photons with a maximum energy of 2.4 GeV were produced from backward-Compton scattering of 351-nm laser photons off 8-GeV electrons in the SPring-8 storage ring. The photons were tagged by measuring the scattered electron energies with a resolution of $\sigma = 15$ MeV. The degree of polarization of the backscattered photon beam was 95 % at 2.4 GeV and 55 % at 1.5 GeV. Half of data were taken with vertically polarized photons and the other half with horizontally polarized photons.

The LEPS spectrometer was optimized to detect K^-K^+ at forward angles (Fig. 1). Charged particles were momentum analyzed by tracing their paths in a magnetic dipole field by means of a silicon-strip vertex detector (SSD) and three drift chambers positioned upstream (DC1) and downstream (DC2, DC3) from the dipole magnet. Electron and positron were removed

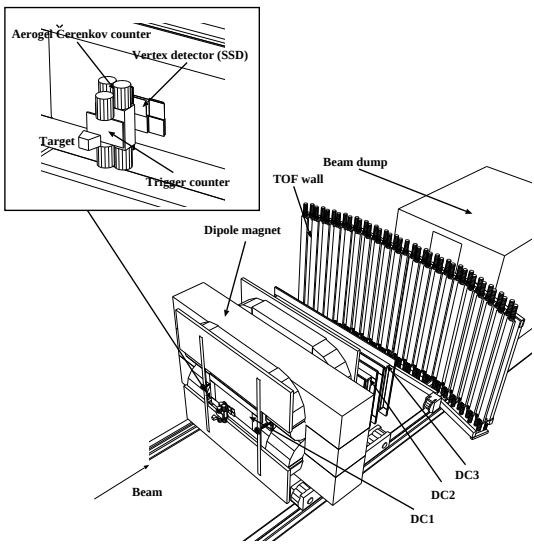


Fig. 1. LEPS detector system.

at the trigger level by means of an aerogel Čerenkov veto counter. The time of flight of each track was measured, the start signal was produced by a plastic-scintillator trigger counter with a thickness of 5 mm placed behind the target cell, and an array of 40 plastic scintillators (TOF wall) placed behind the tracking detectors provided the stop signal. The time-of-flight resolution was about 150 ps for a typical path length of 4 m. By combining time of flight and momentum, the mass of each particle was reconstructed with a resolution (σ) of 30(105) MeV/c^2 for a 1(2) GeV/c GeV/c kaon. A 3 σ momentum dependent mass cut was used to select kaons. A 50-mm thick liquid hydrogen target (LH_2) was used as a proton target to study K^+ photoproduction, and the plastic scintillator trigger counter (C:H $\approx$ 1:1) was used as a neutron target to search for the Θ^+.

3. Results

3.1. $\gamma n \to K^- \Theta^+$

From the total set of 4.3×10^7 events measured in the LEPS detector, 8.0×10^3 events with a K^-K^+ pair were selected. The K^-K^+ pair generated at the plastic scintillator trigger counter was selected by a reconstructed vertex distribution shown in Fig. 2(a). To reduce contribution from nonresonant K^-K^+ productions, events with the photon energy above 2.35 GeV were rejected. About 3.2×10^3 events remained after this cut. The missing mass ($MM_{\gamma KK}$) of the $N(\gamma, K^-K^+)X$ reaction was calculated by assuming

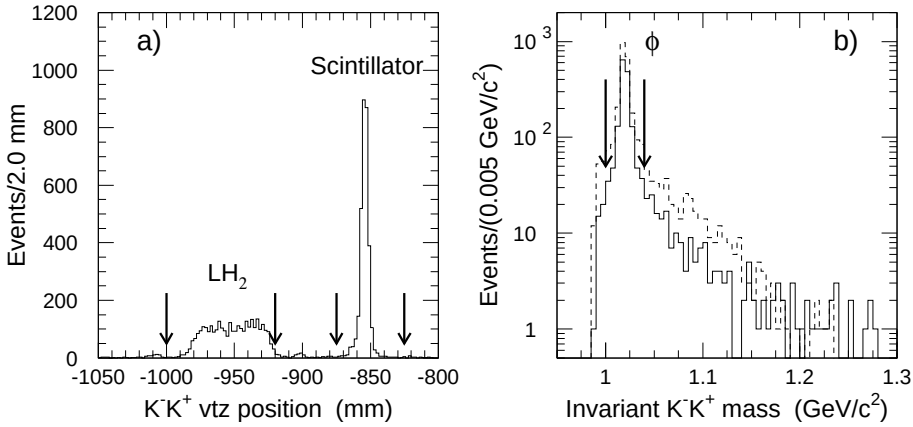


Fig. 2. (a) Vertex position for K^-K^+ events along the photon-beam direction. Cut points to select the plastic scintillator or LH_2 are indicated by arrows. (b) Invariant mass distributions of K^-K^+ for events from the plastic scintillator (solid) and LH_2 (dashed histogram).

that the target nucleon (proton or neutron) has the mean nucleon mass and zero momentum. Subsequently, events with $0.90 < MM_{\gamma KK} < 0.98$ GeV/c^2 were selected. A total of 1.8×10^3 events survived after this cut. Most of the remaining events were due to the photoproduction of the ϕ meson as shown in Fig. 2(b). The ϕ meson mass region of 1.00–1.04 GeV/c^2 was rejected.

In order to discriminate events on neutron from events on proton, the vertex detector SSD was used to detect recoiled proton. The direction and momentum of the nucleon in the final state were calculated from the K^-K^+ momenta. Events with recoiled nucleon out of the SSD acceptance and events with the recoiled nucleon momentum smaller than 0.35 GeV/c^2, since the calculated direction had a large uncertainty, were rejected. Finally, we rejected 108 events which had the SSD hit position agreed with the expected hit position within 45 mm in the vertical or horizontal direction. The total of 109 events satisfied all the selections.

In case of reactions on nucleon in nuclei, the Fermi motion has to be taken into account to obtain appropriate missing mass spectra. To evaluate this effect, we studied the $\gamma n \to K^+\Sigma^- \to K^+\pi^- n$ reaction as an example, where K^+ and π^- were detected. Fig. 3(a) shows a scatter plot of missing mass distributions, $MM_{\gamma K^+}$ *vs* $MM_{\gamma K^+\pi^-}$. The Λ comes from the $\gamma p \to K^+\Lambda$ reaction. Both the missing masses are smeared out due to Fermi motion, however the missing masses have a strong correlation since the target nucleons in the two channels are identical. Therefore, the Fermi motion effect can be corrected and the corrected missing mass ($MM^c_{\gamma K^+}$) of the $N(\gamma,\ K^+)X$ reaction is shown in Fig. 3(b), where the Λ peak is clearly distinguished from the Σ^- peak.

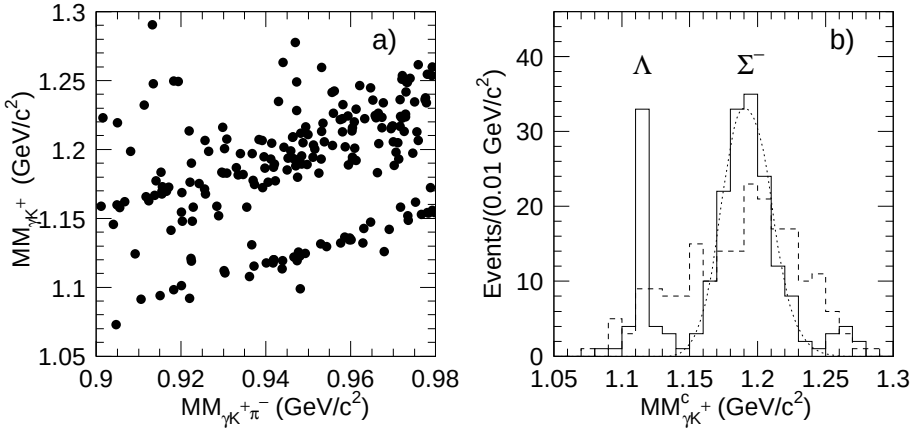


Fig. 3. (a) Scatter plot of $MM_{\gamma K^+}$ *vs* $MM_{\gamma K^+\pi^-}$. (b) Corrected missing mass $MM^c_{\gamma K^+}$ (solid). The dashed histogram is $MM_{\gamma K^+}$ without the Fermi-motion correction.

This technique was also applied to the $\gamma N \to K^+K^-N$ events. In Fig. 4(a) corrected missing mass spectrum ($MM^c_{\gamma K^+}$) for $\gamma n \to K^+K^-n$ is compared with that for $\gamma p \to K^+K^-p$. In the latter case, a clear peak due to the $\gamma p \to K^+\Lambda(1520) \to K^+K^-p$ reaction is observed. The $\Lambda(1520)$ does not exist in the former case, which indicates that reactions on neutron are dominant.

Fig. 4(b) shows the corrected missing mass ($MM^c_{\gamma K^-}$) for $\gamma n \to K^+K^-n$. A prominent peak at 1.54 ± 0.01 GeV/c^2 is found with a width smaller than 25 MeV. There are 36 events in the peak region, $1.54 < MM^c_{\gamma K^-} < 1.57$ GeV/c^2. The peak structure is not observed in the missing mass for events from LH_2. The background level in the peak region is estimated to be $17.0 \pm 2.2 \pm 1.8$, where the first uncertainty is an error in the fitting and the second is a statistical uncertainty. The estimated number of events above the background level is 19.0 ± 2.8, which corresponds to a Gaussian significance of 4.6σ. The measured mass is consistent with the prediction by Diakonov, Petrov, and Polyakov with the chiral soliton model [2]. Detail analysis procedures are found in [3]. The Θ^+ can be interpreted as a molecular meson–baryon resonance or alternatively as an exotic five quark state ($uudd\bar{s}$).

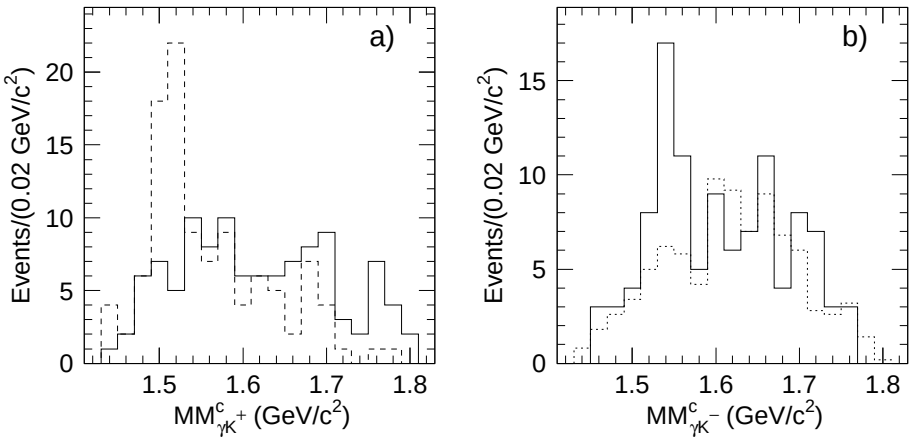


Fig. 4. (a) The $MM^c_{\gamma K^+}$ spectra for $\gamma n \to K^+K^-n$ (solid) and for $\gamma p \to K^+K^-p$ (dashed histogram) from the plastic scintillator. (b) The $MM^c_{\gamma K^-}$ spectra for $\gamma n \to K^+K^-n$ (solid) from the plastic scintillator and for $\gamma p \to K^+K^-p$ (dashed histogram) from LH_2 normalized by a fit in the region above 1.59 GeV/c^2.

Recently, results of the observation of the Θ^+ from other experiments are appearing. The DIANA collaboration at ITEP announced results from an analysis of bubble-chamber data for the reaction $K^+n \to K^0p$, where the neutron is bound in a xenon nucleus. A peak with a width narrower than 9 MeV was observed at 1.539 ± 0.002 GeV/c^2 in the invariant mass of K^0p [4].

The CLAS collaboration at Jefferson Lab. observed a peak with a width of 21 MeV at 1.542 ± 0.005 GeV/c^2 in the invariant mass of K^+n for the $\gamma d \to K^+K^-pn$ reaction [5]. The SAPHIR collaboration at ELSA also observed a peak with a width smaller than 25 MeV/c^2 at $1.540 \pm 0.004 \pm 0.002$ GeV/c^2 in the invariant mass of K^+n for the $\gamma p \to K^+K^0_s n$ reaction [6]. These results confirmed the existence of the Θ^+, which leads us to the new fact that 5-quark baryons can exist.

3.2. K^+ photoproduction

Strangeness photoproduction is a powerful tool to obtain a deeper insight into baryon resonances. Of special interest are nucleon resonances that have been predicted in quark models and for which no experimental evidence has been found with the π-induced or π-production reactions. Some of these resonances could couple strongly to the $K\Lambda$ and $K\Sigma$ channels. In order to understand the problem of such missing resonances, it is interesting to experimentally study the $p(\gamma, K^+)\Lambda$ and $p(\gamma, K^+)\Sigma^0$ reactions. Especially, spin observables, such as the photon beam asymmetry are new candidates for the study. Fig. 5 shows the missing mass spectrum of the $p(\gamma, K^+)X$ reaction, where Λ, Σ^0, $\Lambda(1405)/\Sigma^0(1385)$, and $\Lambda(1520)$ are observed. We

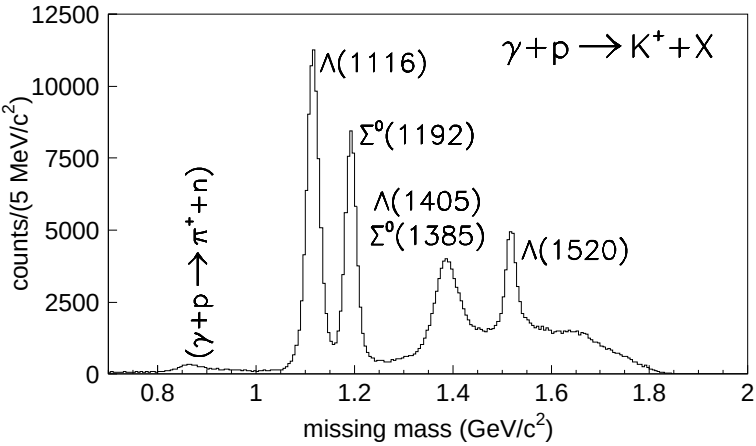


Fig. 5. Missing mass for the $p(\gamma, K^+)X$ reaction. A small bump around 0.9 GeV/c^2 is due to particle mis-identification.

measured the photon beam asymmetries for the $p(\gamma, K^+)\Lambda$ and $p(\gamma, K^+)\Sigma^0$ reactions at $E_\gamma = 1.5$–2.4 GeV and $0.6 < \cos(\theta^{\mathrm{c.m.}}_{K^+}) < 1.0$ as shown in Fig. 6 [7]. The measured photon beam asymmetries are positive and gradually increase with rising photon energy. Currently, there is no theoretical model which reproduces the data perfectly. It could indicate that the freedoms are

too large and that fitting to cross section data only does not give sufficient boundary conditions. The photon beam asymmetries presented here are great assets to stimulate and guide future theoretical works.

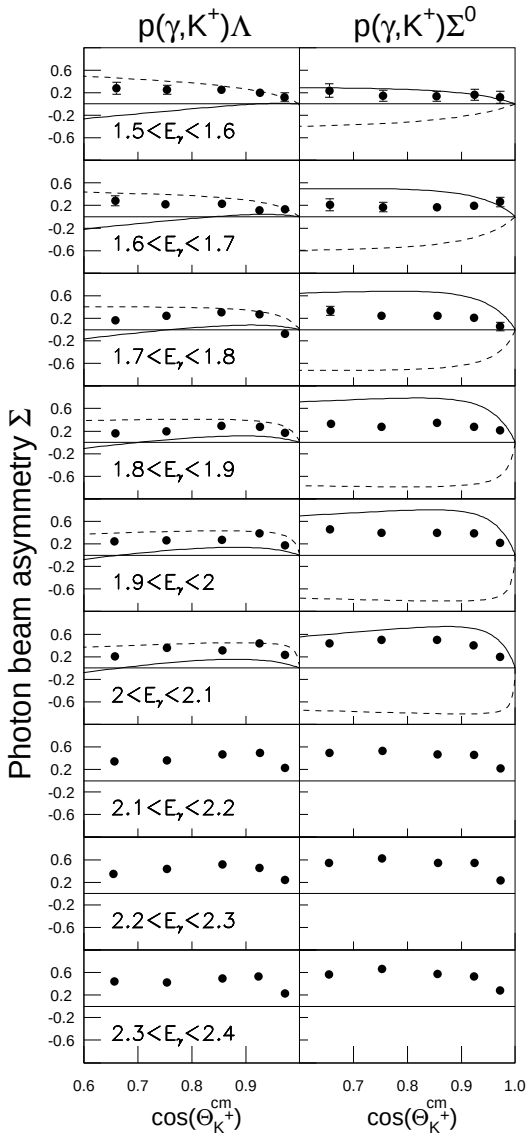


Fig. 6. Photon beam asymmetries for the $p(\gamma,\ K^+)\Lambda$ (left) and $p(\gamma,\ K^+)\Sigma^0$ (right) reactions as a function of $\cos(\theta^{\mathrm{c.m.}}_{K^+})$, where $\theta^{c.m.}_{K^+}$ is an angle measured with respect to the direction of photon. Theoretical predictions using the KAON-MAID program [8] (dashed lines) and by Janssen *et al.* [9,10] (solid lines) are compared with the experimental data.

4. Summary

We discovered 5-quark baryon Θ^+ with $S = +1$ in photoproduction from the neutron in ^{12}C at LEPS of SPring-8. The mass and width of the Θ^+ were 1.54 ± 0.01 GeV/c^2 and smaller than 25 MeV/c^2, respectively. The mass is consistent with the prediction by Diakonov, Petrov, and Polyakov with the chiral soliton model. Results appearing recently from other experiments confirmed the existence of the Θ^+. The Θ^+ can be interpreted as a molecular meson–baryon resonance or alternatively as an exotic five quark state $(uudd\bar{s})$. Photon beam asymmetries for the $p(\gamma,\ K^+)\Lambda$ and $p(\gamma,\ K^+)\Sigma^0$ reactions were measured at $E_\gamma = 1.5$–2.4 GeV and $0.6 < \cos(\theta^{\mathrm{c.m.}}_{K^+}) < 1.0$ by using linearly polarized photon beam. The measured asymmetries are positive and gradually increase with rising photon energy. There is no theoretical prediction which perfectly reproduces the measurements. Including the new results in the development of theoretical models is crucial for understanding the reaction mechanism and to test the presence of missing resonances.

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