Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron

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The $\gamma n \rightarrow K^+ K^- n$ reaction on ^{12}C has been studied by measuring both K^+ and K^- at forward angles. A sharp baryon resonance peak was observed at 1.54 ± 0.01 GeV/c^2 with a width smaller than 25 MeV/c^2 and a Gaussian significance of 4.6σ. The strangeness quantum number (S) of the baryon resonance is $+1$. It can be interpreted as a molecular meson-baryon resonance or alternatively as an exotic five-quark state ($uudd\bar{s}$) that decays into a K^+ and a neutron. The resonance is consistent with the lowest member of an antidecuplet of baryons predicted by the chiral soliton model.

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The search for baryon resonances with the strangeness quantum number $S = +1$ that cannot be formed by three quarks has a long and interesting history. In fact, the summary of the $S = +1$ baryon resonance searches has been dropped from the Particle Data Group (PDG) listings although the possible exotic resonances were noted in the 1986 baryon listings [1]. Most of the previous searches were made using the partial wave analyses of kaon-nucleon (KN) scatterings [2]. These searches resulted in two possibilities, the isoscalar $Z_0(1780)$ and $Z_0(1865)$, for which the evidence of the existence was reviewed to be poor by PDG.

The present work was motivated in part by the recent work by Diakonov, Petrov, and Polyakov [3] who studied antidecuplet baryons using the chiral soliton model. The mass splittings of the established octet and decuplet were reproduced within accuracy of 1% in this model, and those of the new antidecuplet were also estimated using the nucleon sigma term [4] and the current quark-mass ratios. The antidecuplet was anchored to the mass of the $P_{11}(1710)$ nucleon resonance, giving the Z^+ (spin 1/2, isospin 0, and $S = +1$) a mass of $\sim$1530 MeV/c^2 and a total width of less than 15 MeV/c^2. The $S = +1$ baryon resonances in this mass region have not been searched for in the KN scattering experiments in the past because momenta of kaons were too high as pointed out in Refs. [3,5].

The concept of a molecular meson-baryon bound state has been proposed by Refs. [6–8] in conjunction with the well-known $\Lambda(1405)$ particle. The mass spectrum of the $\Lambda(1405)$ can be dynamically generated [6,7] suggesting that this "particle" can be described as a molecular meson-baryon bound state with a quark configuration $uuds\bar{u}$. However, the validity of this assumption is not

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solid and should be checked by measuring the $\Lambda(1405)$ decay [6,7], of which experimental data are scarce. Moreover, the same quantum numbers for the $\Lambda(1405)$ can be achieved with a quark configuration *uds*. This ambiguity is not present in the case of the proposed Z^+ resonance with a quark configuration $uudd\bar{s}$. In this Letter we report the experimental evidence for a narrow resonance with $S = +1$ which can be interpreted as the predicted exotic Z^+ state.

The experiment was carried out at the Laser-Electron Photon facility at SPring-8 (LEPS) [9–11]. Photons were produced by Compton backscattering of laser photons from 8 GeV electrons in the SPring-8 storage ring. Using a 351-nm Ar laser, photons with a maximum energy of 2.4 GeV were produced. Electrons that were participants in the backscattering process were momentum analyzed by a bending magnet of the SPring-8 storage ring, and detected by a tagging counter inside the ring to get the photon energy with a resolution (σ) of 15 MeV. Only photons with energies above 1.5 GeV were tagged. The typical photon flux was $\sim 10^6$ s^{-1}.

A 0.5-cm thick plastic scintillator (SC) which was composed of hydrogen and carbon nuclei (C:H $\approx$ 1:1) was used as a target in the present experiment (see Ref. [9]). The SC was located 9.5 cm downstream from the 5 cm thick liquid-hydrogen (LH_2) target used for studying the photoproduction of ϕ mesons. In fact, the two experiments were carried out simultaneously. Since this Letter concentrates on the study of events generated from neutrons in carbon nuclei at the SC, a comparison between events from the LH_2 and the SC selected under the same conditions, with only a change in the software condition on the reconstructed vertex position (vtz) along the beam axis, provides a good tool to distinguish contributions from protons and neutrons.

A silicon-strip vertex detector (SSD) and three drift chambers were used to track charged particles through a dipole magnet with a field strength of 0.7 T. The SSD consists of single-sided silicon-strip detectors (vertical and horizontal planes) with the strip pitch of 120 μm. The first drift chamber located before the magnet consists of six wire planes (three vertical planes, two planes at $+45°$, and one plane at $-45°$), and the other two drift chambers after the magnet consist of five planes (two vertical planes, two planes at $+30°$, and one plane at $-30°$). A time-of-flight (TOF) scintillator array was positioned 3 m behind the dipole magnet. Electron-positron pairs produced at very forward angles were blocked by lead bars which were set horizontally along the median plane inside the magnet gap. Electrons and positrons that escaped from the blocker and pions with a momentum higher than $\sim$0.6 GeV/c were vetoed online by an aerogel Cerenkov counter located downstream of the SC.

The angular coverage of the spectrometer was about ± 0.4 rad and ± 0.2 rad in the horizontal and vertical directions, respectively. The momentum resolution (σ) for 1 GeV/c particles was 6 MeV/c. The timing resolution (σ) of the TOF was 150 psec for a typical flight length of 4 m from the target to the TOF. Particle identification was made within 3σ of the momentum-dependent mass resolution, which was about 30 MeV/c^2 for a 1 GeV/c kaon.

The design of the LEPS detector is optimized for measuring ϕ mesons produced near the threshold energy at forward angles by detecting the K^+K^- pair from the ϕ decay. These measurements will be reported in a separate article. Here we discuss the detection of K^+K^- pairs generated at the SC. 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. As shown in Fig. 1(a), a cut on the vtz cleanly selected events that originate from a reaction at the SC, which accounted for about half of the K^+K^--pair events.

To reduce contributions from nonresonant K^+K^- productions for which the phase space increases quadratically with the photon energy from the production threshold, events with the photon energy above 2.35 GeV were rejected. About 3.2×10^3 events remained after this cut. The missing-mass $MM_{\gamma K^+K^-}$ of the $N(\gamma, K^+K^-)X$ reaction was calculated by assuming that the target nucleon (proton or neutron) has the mean nucleon mass of 0.9389 GeV/c^2 (M_N) and zero momentum. Subsequently, events with $0.90 < MM_{\gamma K^+K^-} < 0.98$ GeV/c^2 were selected. A total of 1.8×10^3 events survived after this cut. Most of the remaining events ($\sim$ 85%) were due to the photoproduction of the ϕ meson. They were eliminated by removing the events with the invariant K^+K^- mass from 1.00 to 1.04 GeV/c^2 for the ϕ [Fig. 1(b)].

In order to eliminate photonuclear reactions of $\gamma p \rightarrow K^+K^-p$ on protons in ^{12}C and ^{1}H at the SC, the recoiled protons were detected by the SSD. The direction and momentum of the nucleon in the final state was calculated from the K^+ and K^- momenta, and such events in which the recoiled nucleon was out of the SSD acceptance were rejected. Events were rejected if the momentum of the nucleon was smaller than 0.35 GeV/c since

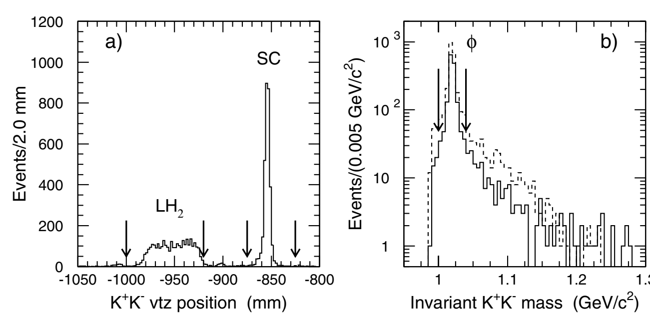

FIG. 1. (a) Vertex position (vtz) for K^+K^- events along the photon-beam direction. Cut points to select the SC events or the LH_2 events are indicated by the arrows. (b) Invariant K^-K^+ mass distributions for the SC events (solid histogram) and the LH_2 events (dashed histogram). Cut points to exclude ϕ contributions are indicated by the arrows.

the calculated direction had a large uncertainty in this case. Finally, we rejected 108 events for which the hit position in the SSD agreed with the expected hit position within 45 mm in the vertical or horizontal direction. The cut points correspond to about $\pm 2\sigma$ resolution for events that are affected by the Fermi motion. A total of 109 events satisfied all the selection criteria. We call this set of events the "signal sample."

In case of reactions on nucleons in nuclei, the Fermi motion has to be taken into account to obtain appropriate missing-mass spectra. To evaluate this effect, we studied the $\gamma n \rightarrow K^+\Sigma^- \rightarrow K^+\pi^- n$ sequential process as an example, where the K^+ and π^- were detected. The missing masses, $MM_{\gamma K^+}$ and $MM_{\gamma K^+\pi^-}$, were obtained for the $N(\gamma, K^+)X$ and $N(\gamma, K^+\pi^-)N$ channels by assuming that the nucleon in ^{12}C is at rest with the mass equal to M_N. Both the missing masses are smeared out due to the Fermi motion of nucleons in ^{12}C. However, since the nucleons in the two channels are identical, the two missing masses have a strong correlation as shown in Fig. 2(a). Accordingly, the missing mass corrected for the Fermi motion, $MM^c_{\gamma K^+}$, is deduced as

$$MM^c_{\gamma K^+} = MM_{\gamma K^+} - MM_{\gamma K^+\pi^-} + M_N. \qquad (1)$$

The correction in Eq. (1) compensates spreads not only due to the Fermi motion but also due to the experimental resolutions and the binding energy of the nucleon in the initial state, although the Fermi motion effect is the major contribution here. Note that this correction is not a good approximation for events with $MM_{\gamma K^+\pi^-}$ far from the nucleon rest mass. The missing-mass distributions before and after the correction are compared in Fig. 2(b). Only after the correction, the Λ (from $\gamma p \rightarrow K^+\Lambda \rightarrow K^+\pi^- p$) and the Σ^- peaks are separated. The correction is good in case of a decay with a small Q value, where the velocity of the hyperon is nearly the same as that of the decaying nucleon. This is seen in the small width of the Λ in the missing-mass spectrum in Fig. 2(b), where about half of the contributions are due to reactions on protons in ^{12}C. On the other hand, the large width of the mass spectrum for the Σ^- is due to the imperfection of the correction caused by a large Q value. The spectrum with a measured width (σ) of 18 MeV$/c^2$ is well reproduced by a Monte Carlo simulation using the impulse approximation for the reaction from a neutron whose momentum distribution is generated according to a harmonic oscillator potential. The Monte Carlo simulation shows that the width is dominated by incomplete cancellation of the Fermi motion effect. Contributions of the binding energy in ^{12}C to the peak position and the width in the corrected spectrum are likely smaller than 10 MeV$/c^2$.

The missing-mass $MM^c_{\gamma K^\pm}$ for K^+K^- events is corrected for the Fermi motion in the similar procedure. The corrected missing mass is given by

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

In Fig. 3(a), the corrected K^+ missing-mass distribution for the 109 events that satisfy all the selection conditions is compared with that for the 108 events for which a coincident proton hit was detected in the SSD. In the latter case, a clear peak due to the $\gamma + p \rightarrow K^+\Lambda(1520) \rightarrow K^+K^-p$ reaction is observed. The $\Lambda(1520)$ peak does not exist in the case that the proton-rejection cut in the SSD is applied as shown in the signal sample. This indicates that the signal sample is dominated by events produced by reactions on neutrons.

Figure 3(b) shows the corrected K^- missing-mass distribution of the signal sample. A prominent peak at 1.54 GeV$/c^2$ is found. It contains 36 events in the peak region $1.51 \leq MM^c_{\gamma K^-} < 1.57$ GeV$/c^2$. The broad background centered at $\sim$1.6 GeV$/c^2$ is most likely due to nonresonant K^+K^- production because the events in the bump do not show any noticeable structure in the K^+ missing-mass nor in the invariant K^+K^- mass spectra and the beam-energy dependence of the production rate reflects the phase space expansion with the energy. To

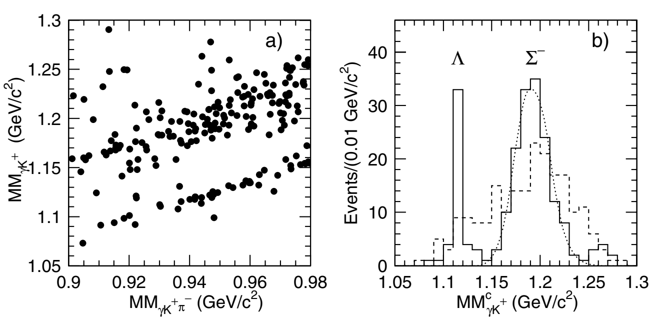

FIG. 2. (a) A scatter plot of $MM_{\gamma K^+}$ vs $MM_{\gamma K^+\pi^-}$ for $K^+\pi^-$ photoproductions at the SC. (b) The missing mass, $MM^c_{\gamma K^+}$, spectra for the $K^+\pi^-$ events from the SC (solid histogram) and for Monte Carlo events for the $\gamma n \rightarrow K^+\Sigma^-$ channel (dotted curve) calculated via Eq. (1). The dashed histogram shows the missing mass spectrum without the Fermi-motion correction, $MM_{\gamma K^+}$ the projection of the events in (a) on to the vertical axis.

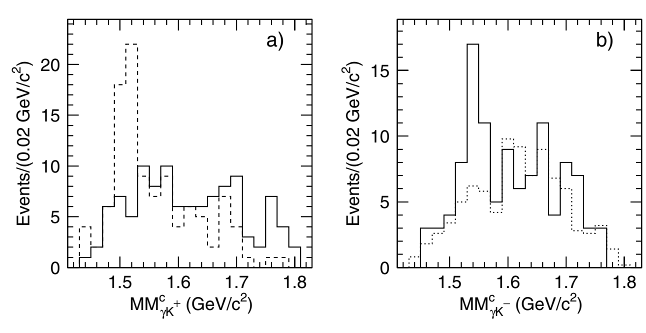

FIG. 3. (a) The $MM^c_{\gamma K^+}$ spectrum [Eq. (2)] for K^+K^- productions for the signal sample (solid histogram) and for events from the SC with a proton hit in the SSD (dashed histogram). (b) The $MM^c_{\gamma K^-}$ spectrum for the signal sample (solid histogram) and for events from the LH$_2$ (dotted histogram) normalized by a fit in the region above 1.59 GeV$/c^2$.

estimate the background level due to the nonresonant K^+K^- production in the peak region of $1.51 \leq MM^c_{\gamma K^-} < 1.57$ GeV$/c^2$, 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. For the event selection, we applied the same conditions as for the signal selection except that the vtz window was shifted to the LH_2 position and a proton hit in the SSD was allowed. The $\Lambda(1520)$ contribution in the LH_2 sample was eliminated by rejecting events with $1.51 \leq MM^c_{\gamma K^+} < 1.53$ GeV$/c^2$ because the $\Lambda(1520)$ contribution was removed from the signal sample by the requirement of no-proton hit in the SSD. The best fit with a χ^2 of 7.2 for 8 degrees of freedom is obtained with a scale factor of 0.20 as shown with a dotted histogram in Fig. 3(b). Note that the acceptance of the kaon pairs from the LH_2 is about 10% smaller than that from the SC. However, the difference in the two acceptances does not depend on $MM^c_{\gamma K^-}$ very much, and its effect on the background estimation is negligible.

The 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 events above the background level is 19.0 ± 2.8, which corresponds to a Gaussian significance of $4.6^{+1.2}_{-1.0}\sigma$ $(19.0/\sqrt{17.0} = 4.6)$. After subtracting the background from the signal sample, the spectrum in the region of $1.47 \leq MM^c_{\gamma K^-} < 1.61$ GeV$/c^2$ was compared with Monte Carlo simulations assuming a Breit-Wigner function for a resonance distribution. The best fit to the spectrum gives the mass of the resonance to be 1.54 ± 0.01 GeV$/c^2$, where the uncertainty is statistical only. The systematic error was estimated to be 5 MeV$/c^2$ from which the observed Σ^- peak position was 5 MeV$/c^2$ smaller than the PDG value of 1.197 GeV$/c^2$. However, there could be a small shift due to nuclear medium effects since the observed resonance was produced in ^{12}C. This point will be cleared up by experiments using a deuterium target or in other reactions [3,5]. 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 25 MeV$/c^2$ with a confidence level of 90%.

To make sure that the observed peak is not due to particle misidentification of (one of) the kaons, the mass cut was tightened from 3σ to 2σ. One event in the peak was lost. This is consistent with the statistical expectation due to a tightened cut. Therefore, particle misidentification as a source of the peak is unlikely. It was also confirmed that the peak was not generated by intentionally selecting pions and by assuming the kaon mass in the missing-mass calculations. The $MM^c_{\gamma K^-}$ distributions for events both at the ϕ resonance and its tails were checked. The shapes of the distributions were similar to that for the LH_2 background sample. Thus, the observed peak is not due to the effect of the tails of the ϕ resonance. No statistically significant excess was found in the peak region for the events from the SC for which a proton hit was found in the SSD. This further confirms that the observed peak is due to the γn reactions.

In conclusion, we have performed a search for an $S = +1$ baryon resonance in the K^- missing-mass spectrum of the $\gamma n \to K^+K^-n$ reaction on ^{12}C, using a newly built photon-beam facility at the SPring-8. A sharp baryon resonance peak has been found at 1.54 ± 0.01 GeV$/c^2$ in the K^- missing-mass spectrum that is corrected for the Fermi motion. The Gaussian significance of the peak is 4.6σ and the width is estimated to be smaller than 25 MeV$/c^2$. This strongly indicates the existence of an $S = +1$ resonance which may be attributed to the molecular meson-baryon resonance or alternatively as an exotic five-quark baryon proposed as the Z^+.

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