Recent results from LEPS*

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Abstract Photoproduction of baryons with strangeness, such as the Σ(1385), Λ(1520) and possibly the Θ^+, are described from measurements at the LEPS/SPring-8 facility in Japan. Linearly polarized photons in the energy range of 1.5–2.4 GeV, along with the forward-angle kinematics at LEPS, provide unique data to learn about these baryons, which are non-perturbative solutions of QCD.

Key words photoproduction, baryons, mesons, exotic, pentaquark

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1 Introduction

LEPS is a photoproduction experiment located at the SPring-8 facility in Japan [1]. Photons in the energy range of 1.5–2.4 GeV strike a target of either hydrogen or deuterium, producing mesons and baryons that are detected downstream. One of the primary goals of the LEPS program is to measure reactions with strangeness in the final state, by detecting kaons or strange baryons (via their decay particles). From these measurements, we learn more about nucleon resonances and especially those with strong coupling to strange-particle decays. This, in turn, helps us to understand non-perturbative QCD by comparing the resonances found by experiment to the spectrum of resonances predicted by, say, lattice gauge theory.

Also of interest is the search for new rare particles which might be produced in small quantities (or at specific kinematics) and hence could have been missed by earlier bubble-chamber experiments. The so-called Θ^+ pentaquark is one example of an exotic baryon, made up of four light quarks and one strange anti-quark, which was not seen in previous searches. The existence of the Θ^+ has been predicted by several theoretical models (see the review article [2]). Evidence for the Θ^+ was first presented by LEPS [3].

Even if no new particles are discovered, indirect evidence for new particles can be uncovered using data from LEPS. A clear example is that the linearly polarized photons at LEPS allow the measurement of the beam polarization observable, Σ, which for K^* photoproduction is sensitive to the exchange of a scalar meson in *t*-channel diagrams. This scalar meson, often called the κ-meson, would be the strange-particle partner in the meson nonet that includes the $a_0(980)$ and $f_0(980)$ scalar mesons. The κ-meson is expected to exist, but may have a wide width, similar to the σ-meson. Definitive evidence for the κ-meson from K^* photoproduction at LEPS would fill the still-vacant holes for strange particles in the lowest-mass scalar meson nonet.

Because of the unique forward-angle kinematics of the LEPS detector and the focus on rare strange-particle reactions, there is the possibility of new particles to be discovered there. But regardless of whether new particles are found or not, measurements of rare strange particle production make LEPS a valuable research facility.

2 Review of LEPS results

Figure 1 is a typical spectrum of missing mass for the reaction $\gamma p \to K^+X$ measured at LEPS, showing peaks for the strange baryon resonances (the ground-state Λ and Σ states appear below the 1.3 GeV limit shown here).

The Λ(1520) is particularly prominant on top of a smooth background, presumably from quasifree $K^+\pi^0$ photoproduction. The Λ(1520) has been a topic of intense study at LEPS, in part because it has a similar mass to the Θ^+ (but opposite strangeness). Understanding the reaction mechanism of the Λ(1520) is particularly useful as a guide in searches for the Θ^+.

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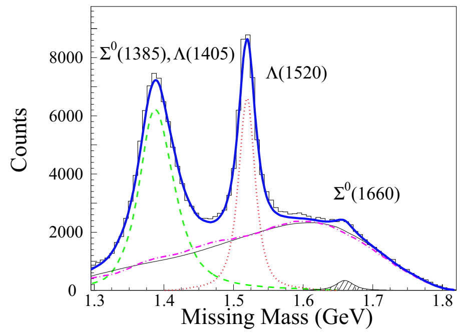

Fig. 1. Missing mass of the p(γ, K^+)X reaction at E_γ=1.5–2.4 GeV and 0.6< $\cos\theta^{K}_{CM}$ <1. The thick solid curve is the result of the fit using the polynomial background (thin solid curve). The dashed, dotted, and hatched curves correspond to Σ^0(1385)/Λ(1405), Λ(1520), and Σ^0(1660) productions, respectively. The dotted-dashed curve is the background obtained by the fit using simulation curves.

The other prominent peak is from a combination of Σ(1385) and Λ(1405), which are difficult to separate in data from the proton. Since the Σ^* resonances have three charge states, the Σ(1385) can be uniquely identified in data from a deuterium target, which will be discussed next. A relevant list of publications from LEPS on strange-baryon production is given in Table 1.

The Σ^* is of interest because it provides a test of $SU(3)$ flavor symmetry within the baryon decuplet group. Many high-quality data exist for photoproduction of the Δ resonance, which can be used to predict, by using $SU(3)$, the coupling constants for photoproduction of the Σ^*. Differences between predictions and measurements provide a gauge of the amount of $SU(3)$ symmetry breaking within the baryon decuplet. Similar studies within the baryon octet have shown $SU(3)$ symmetry breaking on the order of 20%. However, it is not clear if a similar value of $SU(3)$ breaking will occur in the decuplet. Hence, high-statistics measurements of Σ^* photoproduction are needed to test $SU(3)$ symmetry breaking in the baryon decuplet.

Table 1. List of LEPS publication on the photoproduction of hyperons from hydrogen and deuterium targets.

reaction	detection method	results	Refs.
p($\vec{\gamma}$,K^+)Λ, p($\vec{\gamma}$,K^+)Σ	$MM(\gamma N,K^+)$	Σ^{γ}	[4]
p($\vec{\gamma}$,K^+)Λ, p($\vec{\gamma}$,K^+)Σ	$MM(\gamma N,K^+)$	Σ^{γ}, $d\sigma/d\cos\theta$	[5]
n($\vec{\gamma}$,K^+)Σ^-	$MM(\gamma N,K^+)$	Σ^{γ}, $d\sigma/d\cos\theta$	[6]
p($\vec{\gamma}$,K^+)Λ,	$M(p\pi^-)$	Σ^{γ}, $d\sigma/d\cos\theta$	[7]
p($\vec{\gamma}$,K^+)Λ(1405), p($\vec{\gamma}$,K^+)Σ^*(1385)	$M(\Sigma\pi)$	$d\sigma/d\cos\theta$	[8]
n($\vec{\gamma}$,K^+)Σ^{*-}(1385)	$MM(\gamma N,K^+)$	Σ^{γ}, $d\sigma/d\cos\theta$	[9]
p($\vec{\gamma}$,K^+)Λ(1520), n($\vec{\gamma}$,K^0)Λ(1520)	$M(pK)$, $M(KK)$	Σ^{γ}, $d\sigma/d\cos\theta$	[10]
p($\vec{\gamma}$,K^+)Λ(1520)	$MM(\gamma N,K^+)$	Σ^{γ}, $d\sigma/d\cos\theta$	[11]

Σ^{γ}: photon-beam asymmetry. $d\sigma/d\cos\theta$: differential cross section.

$SU(3)$ symmetry relations were used by Oh, Ko and Nakayama in a recent paper [12] on Σ^* photoproduction. Using data on $\rho\Delta$ photoproduction, they predicted the cross sections and beam asymmetries for Σ^* photoproduction.

The Σ^* was identified using the missing mass technique. The K^+ missing mass, $MM(K^+)$, is selected between 1.325 and 1.445 GeV to isolate the Σ^* final state. For these events, the missing mass of the $K^+\pi^-$ system, $MM(K^+\pi^-)$, was fitted (using a Gaussian shape) at the Λ mass. Because of the negative charge of the Σ^{*-} from K^+ photoproduction on the neutron, it is possible to isolate this reaction although care must be taken to simulate all background contributions. See Ref. [9] for more discussion of extracting these cross sections.

After careful consideration of systematic uncertainties, using several independent methods to extract the $K^+\Sigma^{*-}$ yeilds, the results are shown in Fig. 2. The overall systematic uncertainties (not shown) are 12% for the cross sections, shown in the left panel. The systematic uncertainties for the beam asymmetries (right panel) are smaller (about 2%–3%) because many uncertainty factors cancel in the beam asymmetry ratio.

Also shown in Fig. 2 are the theoretical calculations from the model of Ref. [12], averaged over the size of the angular bin shown. Both data and calculations peak near 1.85 GeV, indicating that s-channel diagrams involving nucleon resonances are contributing significantly to the production mechanism. Again, the calculations have not been fit to the data. Rather, the theoretical curves are predictions, based on fits to ρΔ production data and $SU(3)$ flavor symmetry.

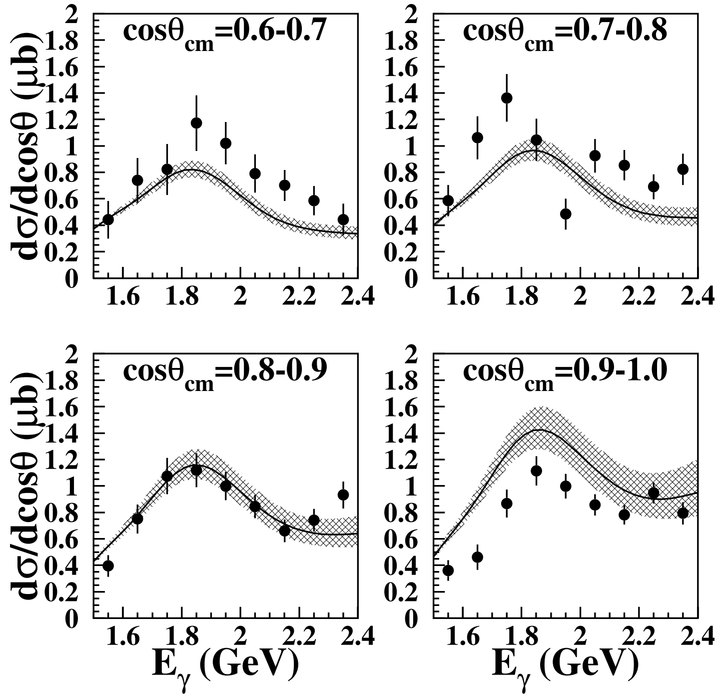

Fig. 2. Cross sections for the reaction of $\gamma n \rightarrow K^+\Sigma^{*-}$ as a function of photon energy. The curve is from the model of Oh [12]. The shaded region extends over the given angular range.

The $K^+\Sigma^{*-}$ beam asymmetries, which are primarily due to interference between different amplitudes, are more negative than predicted by the theoretical curve (bottom half of right panel in Fig. 3). This contrasts strongly with the high, positive values of the beam asymmetry for $K^+\Sigma^-$ photoproduction. The physical meaning of these comparisons are not yet clear, and further theoretical study of these data are necessary.

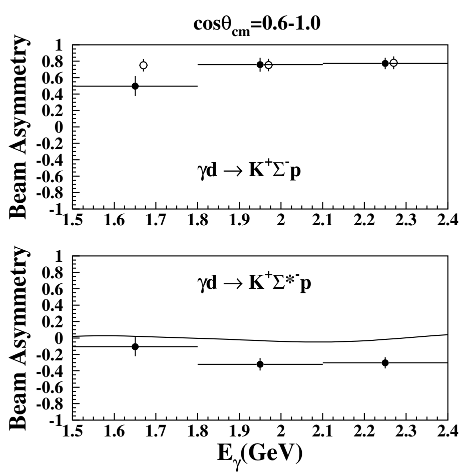

Fig. 3. Photon-beam asymmetry, Σ^γ, for the reactions of $K^+\Sigma^-$ (top) and $K^+\Sigma^{*-}$ (bottom) photoproduction from the deuteron as a function of photon energy. The open points in the top plot are weighted averages [6], which are offset from the bin center for visibility. The curve is from the model of Oh [12].

Figure 3 shows the differential cross sections for various detection methods of $\Lambda(1520)$ photoproduction off the proton. Forward K^+ angles are from detection of a K^+K^- pair (cut on missing mass of the proton), mid-range angles are from detection of a K^+p pair (cut on missing mass of the K^-), and backward angles are from direct detection of of the $\Lambda(1520)$ decay to a K^-p pair. The data are integrated over a wide beam energy bin of 1.9–2.4 GeV photons, in order to minimize statistical uncertainties. The curves shown are from the same model, which includes K exchange (but no K^* exchange) and a contact term [13], and spans the two ends of the beam energy bin. In other words, the data are expected to be at roughly the average of the dashed and dotted curves. The LEPS data were not used as input to the theoretical model, and are in good agreement with these predictions.

On the right side of Fig. 4 is a comparison of the LEPS data [10] with the only other data for this reaction from the 1980 paper by Barber et al. [14]. The LAMP2 data are integrated over photon energies of 2.8–4.8 GeV and kaon angles of 19°–43°. Theoretical calculations [15] based on the chiral unitary model predict that the total cross section should rise above the LAMP2 value with decreasing photon energy, peaking at about 2 GeV. The data in Fig. 4 are not total cross sections, and are both integrated over the same limited angular range, but still the drop in differential cross section is contrary to that expected from the chiral unitary model. It is possible that K* exchange is more important than expected from the dynamically-generated mechanism used in this model.

The importance of the contact term in the model of Nam, Hosaka and Kim [13] cannot be underestimated, as we shall see from the next result.

Figure 5 shows a comparison of differential cross sections, extracted from the K⁻p detection method, for LEPS data [10] off hydrogen and deuterium. Naïvely, one might expect a similar cross section for Λ(1520) photoproduction from the neutron and the proton, resulting in twice the cross section for deuterium. The data show a different story, where the ratio of cross sections off hydrogen and deuterium are measured to be 1.02 ± 0.11, indicating that, for the LEPS kinematics, there is almost no production of Λ(1520) off the neutron. Note that these data are for backward kaon angles, where the Λ(1520) goes forward in the center-of-mass frame.

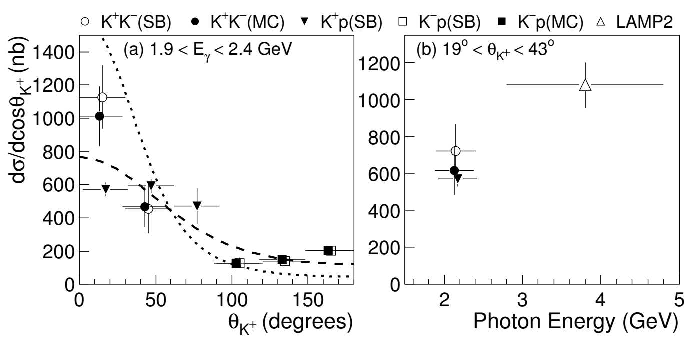

Fig. 4. (a) Differential cross sections from protons at $1.9 < E_\gamma < 2.4$ GeV. The data points are from different detection methods, as given by the key. The curves are from a theoretical prediction [13], for $E_\gamma = 1.85$ GeV (dashed) or $E_\gamma = 2.35$ GeV (dotted). (b) Cross sections from LEPS and LAMP2 [14].

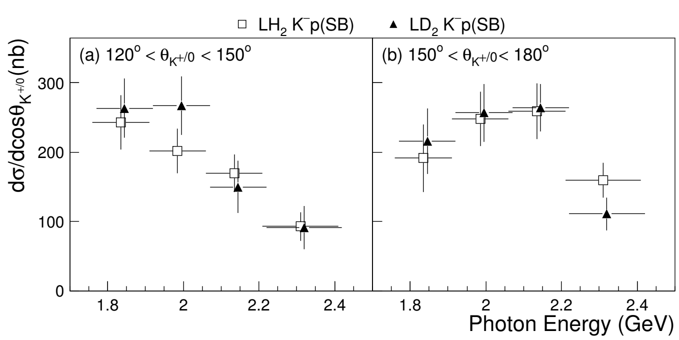

Fig. 5. Differential cross sections [10] at backward kaon angles in the K⁻p detection mode. Results from the hydrogen and deuterium runs are simultaneously plotted as a function of photon energy for the angle ranges shown.

At first, this result seems very surprising, until one compares these data with theoretical calculations. In fact, this result was predicted from the theoretical model of Nam, Hosaka and Kim [13]. The reason for the suppressed photoproduction off the neutron is explained by the dominance of the contact term in this model, which is large for the proton but zero for the neutron. The LEPS data provide an important clue to the photoproduction mechanism for the Λ(1520), at least for backward kaon angles. Other theoretical models, such as those advocating a dominance of t-channel K* exchange [16], must reconcile with the powerful constraint from LEPS given in Fig. 5.

The results of a recently published analysis [17] showing evidence for the Θ^+ are shown in Fig. 6, for the mass of the K⁻p system, and Fig. 7, for the mass of the K⁺n system. Both spectra are for the same events, from the reaction $\gamma d \to K^+K^-X$ where X is the unmeasured pn pair, but projected onto different invariant mass combinations. Event selections used in the analysis are now described.

The K⁺ and K⁻ particles are identified using standard methods (momentum and time-of-flight) and high-momentum pions (a possible source of contamination) are cut out by an aerogel Cerenkov detector just downstream of the target. The ϕ-meson background is removed for events with the K⁺K⁻ invariant mass in the ϕ-peak (1.01–1.03 GeV). A new method, known as the minimum momentum spectator approximation [17] (MMSA), was used to select events where the quasifree appoximation is most valid. A correction for Fermi motion was also applied base on the MMSA, which was verified by simulations. For Fig. 7 it was also required that events with a third track were removed (for the Λ(1520), a proton might be detected but not for the Θ^+ where a neutron is in the final state).

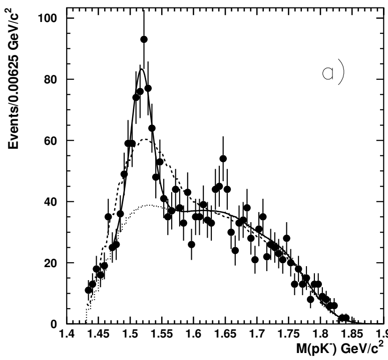

Fig. 6. Invariant mass, $M(\mathrm{pK}^-)$, distribution with a fit to the RMM background spectrum only (dashed line) and with a Gaussian function (solid line). The dotted line is the background. The peak corresponds to the well-known Λ(1520).

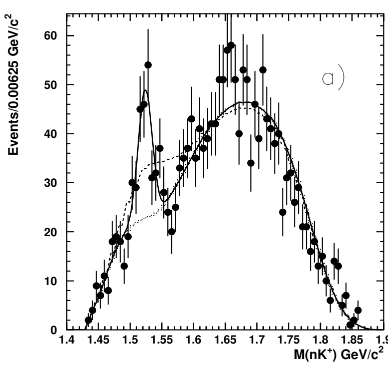

Fig. 7. Invariant mass, $M(\mathrm{nK}^+)$, distribution with a fit to the RMM background spectrum only (dashed line) and with a Gaussian function (solid line). The dotted line is the background. The peak at 1.53 GeV corresponds to the proposed Θ^+.

The shape of the background was estimated using a randomized minimum momentum (RMM) method [17], which again was verified by computer simulations. The RMM provides a random Fermi momentum which essentially smears out any fluctuations. The dashed lines in Figs. 6 and 7 are from the RMM with the peak included and the dotted line is the background assuming that there is a gaussian peak as shown. Using the log-likelihood statistical calculation, a comparison of the the spectra with and without a Gaussian peak results in excess of 5-σ significance to the Θ^+ peak.

While a 5-σ statisical significance is not likely to be due to random fluctuations, it is still not enough to establish the existence of the Θ^+. The results need to be reproducible, and an explanation must be given as to why the Θ^+ is seen only in the LEPS kinematics and not at experiments such as CLAS. The most important thing is that LEPS can reproduce the Θ^+ peak in a second data set with, as nearly possible, the same kinematics. Data for this purpose was taken in 2006, but careful calibration of this data set is still in progress, so no new results are available at the time of writing. It is hoped that a blind analysis (using the same event selection and the same analysis procedure as before) will be presented in early 2010.

One possible explanation of why the Θ^+ might be seen at LEPS but not at CLAS [18] is that the cross section may be very forward-peaked due to a strong t-channel component in the reaction amplitude. It may also be possible that the Θ^+ amplitude interferes constructively with that for ϕ production, which is many times stronger at LEPS forward-angle kinematics that for CLAS. Whatever the explanation, it is important to first establish that the peak is reproducible at LEPS, which is yet to be shown.

Another experiment that has been done at LEPS but is still being analyzed is to measure K^{*0} photoproduction. The reaction is $\gamma\mathrm{p} \to \mathrm{K}^+\pi^-\mathrm{X}$ where X is the missing mass. Fig. 8 shows mass plots for the missing mass and also the invariant mass of the $\mathrm{K}^+\pi^-$ pair. This experiment was done with a new, deep-UV laser, which produces (via Compton backscattering

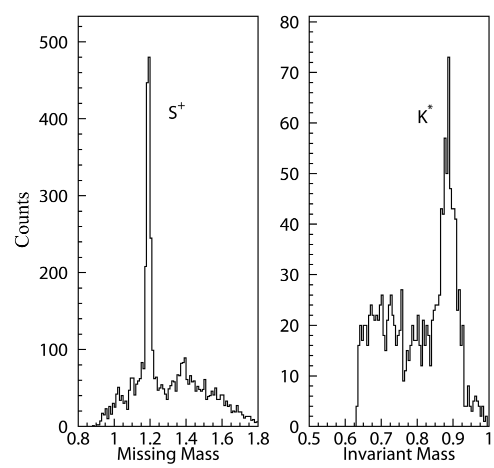

Fig. 8. Preliminary mass plots from the K^* experiment at LEPS, using a photon beam with maxiumum energy 3.0 GeV, for the reaction $\gamma\mathrm{p} \to \mathrm{K}^+\pi^-\Sigma^+$. The events for the invariant mass plot have been cut on the Σ^+ peak.

from the 8 GeV electrons of the SPring-8 storage ring) a higher-energy beam up to 3.0 GeV. Although this produces less beam flux, the higher energy is essential to cross the threshold for K^* photoproduction.

A prominant peak is seen at the Σ^+ mass, on top of a small background from reactions such as $\gamma p \rightarrow K^+Y^*$ where the Y^* decays to $\Sigma^+\pi^-$. The latter reaction also produces a small background under the K^* peak seen in the invariant mass plot, which contains only events in the Σ^+ peak. The prominant peak at the K^* mass shows that the LEPS data will provide cross sections and beam asymmetries for K^* photoproduction at forward angles. CLAS has already published [19] cross sections over a broader angular range but lacks the statistics at forward angles.

The interest in K^* photoproduction is based on theoretical calculations by Oh and Kim [20], where they show that the scalar meson with a strange quark, known as the $\kappa(800)$, contributes to K^* photoproduction through t-channel exchange, dominates at forward angles (i.e. LEPS kinematics). Oh and Kim also show that measurement beam spin asymmetries for this reaction will provide an unambiguous signal that would establish the role of the $\kappa(800)$. The $\kappa(800)$ is the suspected strange partner to the $\sigma(600)$, along with the $a_0(980)$ and $f_0(980)$, in the lowest-mass scalar meson nonet. However, firm evidence of its existence has not yet been established. If the beam asymmetries to be deduced from the LEPS K^* data are close to the predicted values by Oh and Kim, then this would solve this long-standing puzzle of whether the $\kappa(800)$ exists.

3 Summary

The LEPS/SPring-8 facility has provided a wealth of data that provides theorists with the data on strange particle production that they need in order to understand how non-perturbative QCD is manifested in mesons and baryons. In particular, LEPS has led the way with beam asymmetry measurements for photoproduction of KY, KY^* and soon K^*Y final states. Furthermore, LEPS provided the first evidence for the exotic baryon known as the Θ^+, even if its existence is still in question.

The LEPS data on $K^+\Sigma^-$ photoproduction, published in 2009, provides a test of $SU(3)$ symmetry in the lowest-mass baryon decuplet, by comparison to a theoretical model fit to non-strange photoproduction. The results are in good agreement, although better data (and refinement of the theoretical model) is desired.

The LEPS data on $\Lambda(1520)$ photoproduction off hydrogen and deuterium targets have shown the importance of the contact term in the theoretical amplitudes relevant to LEPS kinematics. The same contact term is predicted to play a large role for Θ^+ photoproduction, suppressing production off the proton while allowing production off the neutron. Further evidence for the Θ^+, published in 2009, give 5-σ significance to the peak in the invariant mass of the nK^+ pair. However, the real test is whether this peak is reproducible at LEPS, using a new data set that is still being calibrated.

New data on $K^*\Sigma^+$ photoproduction, which is still being analyzed, will provide beam asymmetries that should establish unambiguously whether the $\kappa(800)$ meson contributes to t-channel diagrams of the reaction mechanism.

Finally, I wish to thank the many contributions from the LEPS collaboration, who have worked hard for the many analyses presented here.

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