Photo-production of neutral kaons on $^{12}$C in the threshold region

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Received 18 July 2006; received in revised form 13 June 2007; accepted 14 June 2007
Available online 19 June 2007

Abstract

The kaon photo-production process on $^{12}$C has been studied by measuring neutral kaons in the photon energy range of 0.8–1.1 GeV. Neutral kaons were identified by the invariant mass constructed from two charged pions emitted in the $K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$ decay channel. The differential and integrated cross sections in the threshold photon energy region were obtained. The obtained momentum spectra were compared with a Spectator model calculation using elementary amplitudes of kaon photo-production given by recent isobar models. The present results provide the first information on the $n(\gamma,K_{0}^{0})\Lambda$ reaction, which is expected to play an important role in constructing models of strangeness production by electromagnetic interactions.

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PACS: 13.60.Lc; 25.20.Lj

Keywords: Photo-production; Strangeness; Neutral kaon; Quasi-free reaction; Cross section; Isobar model

1. Introduction

Strangeness photo-production processes near the threshold have attracted considerable interest in the context of baryon resonances coupled with kaon/hyperon channels. Integrated and differential cross sections as well as hyperon polarizations in the $\gamma + p \rightarrow K^{+} + \Lambda$ and $\gamma + p \rightarrow K^{+} + \Sigma^{0}$ reactions have been measured with high statistics by the SAPHIR Collaboration [1]. A theoretical analysis in the framework of the isobar model has shown that the observed structure around 1900 MeV can be explained well by including a new $D_{13}$ resonance of 1895 MeV [2]. It has also been pointed out that the values of the extracted resonance parameters are strongly influenced by the treatment of the background processes, namely, the choice of the meson and hyperon resonances in the $t$- and $u$-channels, and the adopted recipes for the phenomenological hadronic form factors [3]. Recent CLAS [4,5] and SAPHIR [6] data show a more pronounced structure around 1900 MeV than the old
SAPHIR data. Attempts to fit models to these data have been made [7]; however, new experimental data on spin observables [4,8] and other isospin channels are required to properly construct theoretical models and to obtain clear conclusions on the resonances. Strangeness photo-production processes are expected to reveal rich characteristics of hadron structures and strangeness-involving reactions.

From the viewpoint of the isobar model, the reaction channel, $\gamma + n \rightarrow K^0 + \Lambda$, in the threshold region has the following unique features: (1) The t-channel Born term does not contribute to the reaction channel. (2) The reaction is a mirror of $\gamma + p \rightarrow K^+ + \Lambda$. The coupling constant, $g_{KN}$, has a different sign for the two reactions because of isospin symmetry, $g_{K^0} = -g_{K^+}$. This is also the case for the exchange terms of the isovector hyperon resonance in the n-channel. (3) The contribution of higher mass resonances are suppressed in the threshold region.

It has also been suggested that the angular distribution of neutral kaons could be backward peaked [9]. Furthermore, the amplitude of the $K^0\Lambda$ channel is sensitive only to couplings of neutral particles, and hence can be used to better differentiate diagrams in isobar models. Thus, the neutral reaction channel is expected to play a unique role in the investigation of the photo-production of strangeness, which cannot be fully studied by measuring charged kaon channels.

In this Letter, we report the first measurements of the $(\gamma, K^0)$ reaction on a nucleus ($^{12}$C) using a tagged photon beam. Integrated and differential cross sections are presented as functions of the incident photon energy, $E_\gamma$. The experimental results are compared with predictions of a Spectator model that assumes elementary amplitudes of $\gamma + n \rightarrow K^0 + \Lambda$ given by isobar models.

2. Experiment

The experiment were performed using the internal tagged photon beam facility [10] at the Laboratory of Nuclear Science, Tohoku University (LNS).

The 1.2 GeV electron beam in the Stretch-Booster ring (STB ring) produces bremsstrahlung photons at the internal target of a thin carbon fiber of 15-µm-diameter. The photons were tagged over the energy range of $0.8 \leq E_\gamma \leq 1.1$ GeV with $\Delta E_\gamma = \pm 10$ MeV by bremsstrahlung-recoil electrons, the momenta of which were analyzed by a bending magnet of the STB ring. The average tagged photon rate was $\sim 2.5 \times 10^8 \gamma$/s. The photons bombarded a 2.1 g/cm$^2$ thick graphite target (natural), which was placed at the center of the Neutral Kaon Spectrometer (NKS) as illustrated in Fig. 1.

Charged particles produced at the extraction window of the accelerator ring and the collimator for eliminating the beam halo were swept out by a sweep magnet and were further blocked by concrete shields. The beam line from the sweep magnet to the target was filled with a helium bag to suppress the conversion positron-electron pairs, which was one of the major sources of trigger backgrounds. As shown in Fig. 1, a CsI(pure) counter was placed downstream of the NKS to measure the photon tagging efficiency in separate runs with low intensity beams. The averaged efficiency was measured to be 78 ± 1%.

Neutral kaons were measured by detecting positive and negative pions in coincidence emitted in the $K_S^0 \rightarrow \pi^+\pi^-$ decay channel. The NKS is based on the TAGX spectrometer [11]. It was originally built at the Electron Synchrotron Laboratory of the Institute for Nuclear Study (INS-ES) and re-assembled at LNS. It comprises a dipole magnet of 107-cm-diameter pole and 60-cm gap, straw (SDC), and cylindrical (CDC) drift chambers in a magnetic field of 0.5 Tesla, inner (IH) and outer (OH) plastic scintillator hodoscopes, and a set of veto plastic counters (Veto) in the beam plane. It covers 25% of the whole solid angle.

Since background triggers due to the conversion process along the beam line were dominant, a Veto of 4-cm high was installed in the mid-plane behind the OH counter arrays to suppress the triggers. The trigger rate was typically 100–200 Hz, and more than half of this rate was due to background triggers. The background triggers themselves were due to accidental coincidences between the NKS trigger and the trigger tagger, and were easily rejected by offline analysis.

3. Analysis

The horizontal momentum of a charged particle was reconstructed by the hit position information of the SDC and the CDC using a magnetic field map calculated by a 3D magnetic field program, TOSCA. The vertical component of the trajectory was calculated from the approximate height at the target, which was assumed to be the same as that of the beams, and the hit position at the OH, which was obtained from the time difference between two PMT signals. The time of flight was measured between the IH and the OH, separated by about 1 m. The time resolution was 0.6 ns (rms), which was good enough to separate pions from protons below 0.7 GeV/c, the momentum of the decay pions in the present kinematics. The $e^+e^-$ events were removed by rejecting events with a vertex position upstream of the target.
multi-pion production, \( N \) in Fig. 2(a) and were due to background processes such as all of the events were produced in the target region denoted as in order to achieve a good vertex resolution of 1.7 mm. Almost \( \pi \) in the target region (TG-gated). (c) Invariant mass spectrum of \( \pi^+ \pi^- \) events gated such that the vertex is outside the target denoted by DV. The peak around \( M = 493 \text{ MeV}/c^2 \) can be identified as \( K^0_S \).

Fig. 2. (a) Vertex distribution of \( \pi^+ \pi^- \) events. The figure shows a top view of the target area with the beam traveling from left to right (X-axis) and the Y-axis perpendicular to the beam. Events occur mainly in the target region denoted by TG. (b) Invariant mass spectrum of \( \pi^+ \pi^- \) events gated such that the vertex is in the target region (TG-gated). (c) Invariant mass spectrum of \( \pi^+ \pi^- \) events gated such that the vertex is outside the target denoted by DV. The peak around \( M = 493 \text{ MeV}/c^2 \) can be identified as \( K^0_S \).

Fig. 3. Missing mass spectrum of \( \gamma C \rightarrow K^0 X \) (solid). The background is estimated from the invariant mass region of \( 0.395 < M_{\pi^+\pi^-} < 0.445 \) and \( 0.545 < M_{\pi^+\pi^-} < 0.595 \text{ GeV}/c^2 \) (dashed). The arrow shows the threshold of the quasi-free production.

**Fig. 2(a)** shows the vertex point distribution of \( \pi^+ \pi^- \) events. An opening angle \((\eta)\) cut, \( \cos \eta > -0.8 \), was applied in order to achieve a good vertex resolution of 1.7 mm. Almost all of the events were produced in the target region denoted as TG in Fig. 2(a) and were due to background processes such as multi-pion production, \( N^* \), and \( \rho^0 \). The invariant mass spectrum for these events shows no peak structure, as shown in Fig. 2(b). In contrast, the invariant mass spectrum for events with vertex points in the decay volume region (DV) shows a peak structure at the \( K^0 \) mass, as demonstrated in Fig. 2(c). Since \( K^0_S \) has a relatively long lifetime of \( c\tau = 2.68 \) cm and decays in flight, the \( K^0 \) events are enhanced by selecting vertex points outside the target.

In addition to the vertex position cut, kinematical consistency between the vertex position and the two-body momentum direction was required to further reject mis-reconstructed events. The missing mass spectrum after applying the selection technique is shown in Fig. 3. It shows that measured \( K^0_S \)s are produced in the quasi-free kinematical region.

Momentum spectra of neutral kaons were obtained by subtracting background events, assuming that they have the following two origins: (I) Reaction processes other than \( K^0 \) pro-

duction, such as \( \rho \) production, for which the vertex should be reconstructed in the TG region but was instead reconstructed in the DV region due to the limited vertex resolution. (II) Combinational background of \( \pi^+ \pi^- \), such as \( \pi^+ \) from \( K_S^0 \) decay and \( \pi^- \) from \( \Lambda \) decay. The shapes of the background in the invariant mass and the momentum distributions were calculated from the experimental data for (I) and from a Monte Carlo simulation using Geant4 [12] for (II). The ratio of the background to \( K^0_S \) was obtained by fitting the invariant mass spectra at each photon energy. In Fig. 4(a), the background shapes in the invariant mass spectrum are shown for (I) by a dashed line and for (II) by a dot-dashed line. The background subtracted invariant mass spectrum is shown in Fig. 4(b). The \( K^0 \) momentum spectra before and after the background subtraction are shown in Figs. 5(a) and 5(b), respectively.

The spectrometer acceptance was estimated by a Geant4 simulation. The analysis efficiencies were also estimated based on the simulation, except for the tracking efficiency. The tracking efficiency, which depends on the intrinsic chamber efficiencies and the track-finding algorithm, was estimated to be 67% using pion events for the left and right arms independently. The number of tagged photons for each tagger segment was counted with scalers. The cluster hits and analysis cuts were corrected using the tagger trigger data taken for the same beam condition. The total systematic error was estimated to be \( \pm 15\% \). This large systematic error was due to the strong position dependence of the tracking efficiency due to the high singles rate at forward angles.

4. Results and discussion

The momentum- and angle-integrated cross sections as a function of photon energy for \( K^0 \) are plotted in Fig. 6, in
In Fig. 7, the four obtained momentum spectra of $K^0$ are shown for the two photon energy regions $0.9 < E_γ < 1.0$ GeV and $1.0 < E_γ < 1.1$ GeV and two $K^0$ angular ranges $0.8 < \cos \theta_K^{\text{lab}} < 0.9$ and $0.9 < \cos \theta_K^{\text{lab}} < 1.0$. The quoted errors include statistical errors and the acceptance uncertainty. In the high momentum region at forward angles, the errors become large due to the smaller acceptance.

The obtained experimental results were compared with theoretical calculations using a Spectator model. In this model, the cross section of the quasi-free $γ + N \rightarrow K^{+0} + Y$ was calculated as an incoherent sum of elementary invariant amplitudes ($F$) for the production of individual bound nucleons ($N$). In the laboratory frame the cross section is

$$
\frac{d^2\sigma}{d\Omega dp_K} = \frac{1}{(4\pi)^2} \int d\bar{p}_N \rho(\bar{p}_N) \frac{|F(s,t,\bar{m}_N)|^2}{4 \bar{p}_Y \cdot \bar{p}_N} \times \frac{p_K^2}{E_K E_Y} \delta(E_Y + \bar{E}_N - E_K - E_Y)
$$

$$
= \int d\bar{p}_N \rho(\bar{p}_N) \frac{d\sigma^*}{d\Omega} (W, \cos \theta_K^*, \bar{m}_N) \frac{p_Y^*}{p_K^*} \times \frac{W^2}{p_Y \cdot p_N} \frac{p_K^2}{E_K E_Y} \delta(E_Y + \bar{E}_N - E_K - E_Y),
$$

where $p, \bar{p}$, and $p$ are the 4-momentum vector, 3-momentum vector, and the magnitude of the momentum, respectively. $\bar{E}_N$ denotes the energy of a bound nucleon, which is fixed by the $δ$-function, and $\bar{m}_N$ is the corresponding mass. $W$ is the center-of-mass energy of the incoming photon and the bound nucleon. The variables denoted by $*$ are in the center-of-mass frame of the photon and nucleon. The momentum distribution of the bound nucleons, $\rho(\bar{p}_N)$, is normalized to the effective proton ($Z_{\text{eff}}$) or neutron ($N_{\text{eff}}$) numbers of the target nucleus $A$.

These phenomenological parameters mimic the attenuation effects of the initial photons and the final kaons and $Λ$ (the final state interaction). A value of 4.2 was assumed for both $Z_{\text{eff}}$ and $N_{\text{eff}}$, deduced in a $^{12}\text{C}(γ, K^+)$ experiment in the same energy region [13]. The error of $\pm 0.6$ was not taken into account in the present calculations. The momentum distribution of the nucleons was modeled by the Fermi gas model with $k_F = 0.22$ GeV/c for simplicity.

In Eq. (1), conservation of energy and momentum is required both in the complete (many-body) system and the elementary (2-body) system:

$$
p_Y + p_A = p_K + p_A + p_{A-1},
$$

$$
p_Y + p_N = p_K + p_A.
$$

(2)
(3)

Under these conditions, the energy and momentum of the bound nucleon are

$$
\bar{E}_N = M_A - \sqrt{M_{A-1}^2 + p_N^2},
$$

$$
\bar{p}_N = -\bar{p}_{A-1}.
$$

(4)
(5)

where $M_A$ and $M_{A-1}$ are the masses of the target and residual nuclei, respectively. Since the residual nucleus propagates on its mass-shell, the bound nucleon is off-shell and its energy therefore does not correspond to the on mass-shell value. For
$K^0\Lambda$ production on $^{12}\text{C}$, the mass of the bound nucleon decreases by 2% at $p_N = 0$ GeV/c and 5% at $p_N = 0.22$ GeV/c. This mass reduction makes the two-body center-of-mass energy lower. The kinematical area for integration is therefore smaller, which results in smaller cross sections for the on-mass-shell approximation, $\tilde{E}_N = E_N = \sqrt{p^2_N + m_N^2}$. Additional off-shell effects are given by the in-medium modification of the elementary amplitude. In our approach, a modification is made assuming explicit dependence of the amplitude on the nucleon mass,

$$F(s, t, m_N),$$

rather than adopting the completely relativistic description discussed in Ref. [14]. This can be justified as being due to small variations of $m_N$ in the kinematical region assumed here.

The elementary amplitude was evaluated using the Kaon-Maid (kMAID) [2] and Saclay-Lyon A (SLA) [15] models. Besides the Born terms, these isobar models include $K^*(890)$ and $K_1(1270)$ diagrams, which have been shown to be important for a proper description of the data in the intermediate energy region [16]. In the SLA model, four hyperon and one nucleon resonance are assumed, whereas only four nucleon resonances are included in kMAID. The structure in the hadronic vertices is modeled by the hadronic form factors in kMAID, but point-like hadrons are assumed in SLA.

In the isobar models, the ratios of the electromagnetic transition coupling constants between the charged and neutral particles have to be adjusted before the model is applied to the $K^0\Lambda$ channel. The ratios are known for processes involving a nucleon or a $K^*$ but are unknown for those involving a $K_1$. In kMAID the ratio $r_{KK_1} = g(K_1^0\Lambda p)/g(K_1^+\Lambda p)$ was determined by simultaneously fitting the data for the $p(p, K^+)\Lambda$, $p(p, K^+)\Sigma^0$, and $p(p, K^+)\Sigma^+$ channels. The kMAID model therefore provides predictions for both the $K^0\Lambda$ and $K^0\Sigma^0$ channels. In SLA, however, the ratio $r_{KK_1}$ is free and has to be adjusted for $K^0$ production.

The results of calculations using the kMAID amplitudes are shown in Fig. 7(a)–(d), where the dashed and dot-dashed lines display contributions from the $n(γ, K^0)\Lambda$ process and the sum of all the $K^0$ production processes, including $n(γ, K^0)\Sigma^0$ and $p(γ, K^0)\Sigma^+$ processes, respectively. The dotted, solid, and dot-dashed lines in (e)–(h) show the contributions of the $n(γ, K^0)\Lambda$ process with $r_{KK_1} = -0.447$, $-1.5$, and $-3.4$, respectively.

$K^0\Lambda$ production on $^{12}\text{C}$ has been measured in the momentum range $E_γ < 1.0$ GeV, as shown in Fig. 7. The momentum spectra with those calculated by the models. As shown in Fig. 7(e)–(h), the data from Fig. 7(a)–(d) are compared with the SLA amplitude. The results for three values of the ratio $r_{KK_1}$, $-0.447$, $-1.5$, and $-3.4$, are shown to demonstrate the sensitivity of the cross sections to this parameter. The cross sections are greater for larger $r_{KK_1}$ values. The best result was achieved for $r_{KK_1} = -1.5$, whereas the value $r_{KK_1} = -0.447$ used in the kMAID model overestimates the present results. The value $r_{KK_1} = -3.4$, which gives very similar predictions as kMAID for the elementary cross sections, underestimates the presented experimental data. The SLA can also better describe the spectral shapes in the low $K^0$ momentum region with lower photon energy.

Although $K^0$ angular distributions cannot be directly deduced from the present data due to the limited kinematical acceptance, we evaluated them by comparing the measured momentum spectra with those calculated by the models. As shown in Fig. 8, kMAID and SLA with different $r_{KK_1}$ values give different angular distributions of the elementary $n(γ, K^0)\Lambda$ process in the center-of-mass frame. Converting the center-of-mass frame to the laboratory system, the $K^0$ momentum spectra...
show quite different shapes, with backward $K^0$ in the center-of-mass frame contributing more to the low momentum region in the laboratory system and forward $K^0$ to the higher momentum region because of the Lorentz boost. Since the SLA prediction with $r_{KK} = -1.5$, which represents a gentle backward angular distribution, gives reasonable agreement with the present data, it can be said, without going into the detail of the models, that the present data possibly suggest a slightly backward angular distribution for the elementary $\gamma n \rightarrow K^0 \Lambda$ process, though some part of the low momentum excess is possibly due to $\Sigma$ production.

5. Summary

We have made the first measurements of the integrated and differential cross sections of the $^{12}\text{C}(\gamma, K^0)$ reaction at photon energies below 1.1 GeV, identifying neutral kaons by reconstructing the $K^0_S \rightarrow \pi^+\pi^-$ decay. We found that the integrated cross section is almost the same in magnitude as that of $^{12}\text{C}(\gamma, K^+)$, Quasi-free spectra of the reaction were calculated using elementary amplitudes given by the Kaon-MAID (kMAID) and Saclay-Lyon A (SLA) models, and were compared with the present experimental data. Both models explain the spectra in the threshold region reasonably well, though the SLA model can better account for the excess of the measured cross section in the $K^0$ low momentum region compared with the kMAID calculation. This possibly suggests that the $n(\gamma, K^0)\Lambda$ reaction is more backward peaked in the center-of-mass frame. The present data provide the first information on the unique strangeness photo-production in the neutral channel and demonstrate the importance of the $n(\gamma, K^0)\Lambda$ reaction for the investigation of strangeness photo-production. Further measurements with a deuterium target are underway.

Acknowledgements

The authors wish to thank the scientific and technical staff of LNS for the operation of the accelerator and for experimental supports. We are grateful to Prof. K. Maruyama and Prof. H. Okuno for their help with moving the TAGX spectrometer from the INS to Tohoku University. They also wish to thank Dr. T. Mart for useful discussions and for making available the program code. This work was supported by a Grant-In-Aid for Scientific Research from the Ministry of Education of Japan, Nos. 09034028, 12002001, and 16GS0201. T.T. acknowledges the support from a Grant-In-Aid for Scientific Research from the Ministry of Education of Japan, No. 14740150. P.B. and M.S. acknowledge support from the Grant Agency of the Czech Republic, Grant No. 202/05/2142.

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