Kaon photoproduction on the neutron using deuterium

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The three processes $\gamma+d\to\Lambda^0(\Sigma^0)+K^0+p$ and $\gamma+d\to\Sigma^-+K^++p$ are investigated in the framework of the impulse approximation. The exclusive reactions $d(\gamma,Kp)Y$ where the proton is detected in coincidence with the K^0 or K^+ should provide unique signatures for each of the processes. In most kinematic situations the final-state Yp interaction is insignificant and the elementary cross section for $\gamma+n\to Y+K$ can be reliably extracted. Cross-section estimates are given for several models of the basic production operator.

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In order to obtain reliable predictions of hypernuclear cross sections in kaon electro-magnetic production, knowledge of the elementary process is imperative. There are six basic kaon production reactions on the nucleon: (a) $\gamma+p\to K^++\Lambda^0$, (b) $\gamma+p\to K^++\Sigma^0$, (c) $\gamma+p\to K^0\quad+\Sigma^+$, (d) $\gamma+n\to K^+\quad\Sigma^-$, (e) $\gamma+n\to K^0+\Lambda^0$, (f) $\gamma+n\to K^0+\Sigma^0$. Experimental information, mainly acquired in the 1970s, is available only for the first two channels [1,2], and a number of studies appeared in recent years regarding $K^+\Lambda$ photoproduction [1,3,4]. Due to far less cross-section data being available little is known about the $K^+\Sigma^0$ channel [2]. To gain additional information about isospin dependence it will be necessary to study the process $\gamma n\to K^+\Sigma^-$ for which the elementary operator could look quite different since neither Λ nor its excited states Λ^* can contribute in the intermediate channels. Regarding hypernuclear production [2], Σ^- photoproduction may be preferable over Σ^0, since the Σ^- may be bound deeper in a nucleus due to the additional Coulomb attraction. The experimental situation regarding sigma hypernuclei remains controversial ever since measurements at CERN suggested the existence of narrow sigma structures in $(K^-,\pi^\pm)$ reactions [5]. Even though some information about the sigma-nucleus potential is available from sigma-atom level shifts and widths [6] it is not yet clear if the sigma single-particle potential is deep enough to support bound or quasistable states. A recent experiment reported evidence for a bound sigma state in ^{4}He [7], however, several other experiments at KEK and Brookhaven could not support the existence of narrow sigma states. A recent review of the experimental and theoretical situation can be found in Ref. [8].

Finally, the reactions involving a K^0 in the final state are interesting since the Born terms do not contain a t channel; only kaon resonances such as $K^*(892)$ can contribute to the t channel. Certain kaon resonances in the t channel have been found [4] to significantly affect the value of the coupling constant $g_{K\Lambda N}$ in the process $\gamma p\to K^+\Lambda^0$; thus knowledge of the K^0 production amplitudes should be helpful in sorting out these effects.

In this Brief Report we focus on the last three reactions (d)–(f) using a deuteron target, thus we have: (g) $\gamma+d\to K^++\Sigma^-+p$, (h) $\gamma+d\to K^0+\Lambda^0+p$, (i) $\gamma+d\to K^0+\Sigma^0+p$. We employ the calculational framework of Refs. [9] and [10] to evaluate exclusive differential cross sections where the kaon is detected in coincidence with either the outgoing proton or hyperon in order to provide a unique signal for the process involved. The cross section for the process $\gamma+d\to K+Y+p$ in the deuteron rest frame, in which the photon defines the z axis and the kaon lies in the $x-z$ plane with $\phi_K=0$, is given by

$$d\sigma=(2\pi)^4\frac{M_pM_Y}{8M_dE_\gamma E_KE_YE_p}|\sqrt{2M_d(2\pi)^3}\mathcal{M}_{fi}|^2\delta^{(4)}(P_d+p_\gamma-p_K-p_K-p_Y-p_p)\frac{d^3p_Kd^3p_Yd^3p_p}{(2\pi)^9}\,, \tag{1}$$

where the four-momenta of the deuteron, photon, kaon, hyperon, and proton are denoted by P_d, p_γ, p_K, p_Y, and p_p, respectively. The transition matrix element

$$\mathcal{M}_{fi}=\bar{u}(\mathbf{p}_Y,s_Y)\mathcal{T}_{\gamma K}u(-\mathbf{p}_p,s_p)\Psi^+(\mathbf{p}_p) \tag{2}$$

contains Dirac spinors u and $\bar{u}$, the deuteron wave function $\Psi^+(\mathbf{p}_p)$, and the elementary transition operator $\mathcal{T}_{\gamma K}$. We can write it in the structural form $\mathcal{M}_{fi}=\langle KYp|\mathcal{T}_{\gamma K}|\gamma d\rangle$.

To treat the hyperon-nucleon final-state interaction it is necessary to separate the relative hyperon-nucleon motion (denoted by $\mathbf{r}$ and $\mathbf{q}$) from the c.m. motion (denoted by $\mathbf{R}$ and $\mathbf{P}$). The two-body scattering problem is then solved in the presence of the potential V to obtain the radial part of the wavefunction $u_l(r)$. To facilitate numerical calculations, a complete system of plane waves

$$\int |Y'p'\rangle\langle Y'p'| = \frac{1}{(2\pi)^6}\int d^3P'd^3q'e^{i\mathbf{P}'\cdot(\mathbf{R}-\mathbf{R}')}e^{i\mathbf{q}'\cdot(\mathbf{r}-\mathbf{r}')} = \delta(\mathbf{R}-\mathbf{R}')\delta(\mathbf{r}-\mathbf{r}') \tag{3}$$

is inserted between the distorted state $\langle Yp|$ and the transition operator $\mathcal{T}_{\gamma K}$:

$$\mathcal{M}_{fi} \to \tilde{\mathcal{M}}_{fi} = \langle Yp| \int |Y'p'\rangle\langle Y'p'K|\mathcal{T}_{\gamma K}|\gamma d\rangle \ . \tag{4}$$

The matrix element $\langle Yp|Y'p'\rangle$ in Eq. (4) can be written as

$$\begin{aligned}\langle Yp|Y'p'\rangle &= \frac{1}{(2\pi)^6}\int d^3Rd^3r\Psi^*(\mathbf{r})e^{-i\mathbf{P}\cdot\mathbf{R}}e^{i\mathbf{P}'\cdot\mathbf{R}+i\mathbf{q}'\cdot\mathbf{r}} \\ &= \delta(\mathbf{P}-\mathbf{P}')\delta(\mathbf{q}-\mathbf{q}') + \frac{\delta(\mathbf{P}-\mathbf{P}')}{(2\pi)^3}\sum_l (2l+1)i^{-l}\int d^3r\, e^{i\mathbf{q}'\cdot\mathbf{r}}\left[\frac{u_l(r)}{r} - j_l(qr)\right]P_l(\cos\theta)\end{aligned} \tag{5}$$

where for improved convergence we have added and subtracted the plane wave $e^{-i\mathbf{q}\cdot\mathbf{r}}$ from Ψ^*. Using Eqs. (1)–(5) we can evaluate the exclusive cross section $d^3\sigma/d\Omega_K d\Omega_p dp_p$ for the deuteron process.

The cross section for the elementary process $\gamma + n \to K + Y$ is given by

$$d\sigma_{\text{elem}} = (2\pi)^4 \frac{M_n M_Y}{4E_K E_Y p_\gamma \cdot p_n} |\mathcal{M}_{fi}^{\text{elem}}|^2 \delta^{(4)}(p_\gamma + p_n - p_K - p_Y) \frac{d^3p_K d^3p_Y}{(2\pi)^6} \ , \tag{6}$$

where the elementary transition matrix element is

$$\mathcal{M}_{fi}^{\text{elem}} = \bar{u}(\mathbf{p}_Y, s_Y)\mathcal{T}_{\gamma K} u(\mathbf{p}_n, s_n) \ . \tag{7}$$

From Eqs. (1),(2),(4),(6),(7) we can obtain

$$d\sigma = \frac{M_p}{M_n}\frac{p_\gamma\cdot(P_d - p_p)}{E_\gamma E_p}\frac{|\tilde{\mathcal{M}}_{fi}|^2}{|\mathcal{M}_{fi}^{\text{elem}}|^2} d^3p_p d\sigma_{\text{elem}} \ , \tag{8}$$

where we have used the delta-function property

$$\begin{aligned}&\delta^{(4)}(P_d + p_\gamma - p_K - p_Y - p_p) \\ &\quad = \int \delta^{(4)}(p_\gamma + p_n - p_K - p_Y)\delta^{(4)}(P_d - p_n - p_p)d^4p_n\end{aligned}$$

in arriving at the final expression. Eq. (8) shows that in order to extract the basic production cross section from the deuteron cross section, the effects of final-state interaction need to be small, so that we can approximate $\tilde{\mathcal{M}}_{fi}$ by $\mathcal{M}_{fi}$. It is indeed the case as found in Refs. [9] and [10] as well as Refs. [11] and [12] as long as one stays away from threshold. Furthermore, if we neglect the off-shell effects of the propagating neutron as well as the proton-neutron mass difference, we can obtain the usual factorized nonrelativistic expression:

$$d\sigma = (1 + \beta_p \cos\theta_p)|\Psi^+(\mathbf{p}_p)|^2 d^3p_p d\sigma_{\text{elem}} \tag{9}$$

with $\beta_p = |\mathbf{p}_p|/E_p$. Equation (9) establishes the relation between the counting rate, elementary cross section $d\sigma_{\text{elem}}$, and the flux $(1+\beta_p\cos\theta_p)$ of the incoming photons seen by the moving target nucleon, whose number is $|\Psi^+(\mathbf{p}_p)|^2 d^3p_p$. The spectator nucleon model becomes evident in this formula. However, in order to extract the elementary cross section in the conventional photon-neutron c.m. frame rather than the laboratory frame of the deuteron a transformation is required which involves a Lorentz boost along the direction defined by $(\mathbf{p}_\gamma - \mathbf{p}_p)$. This Jacobian is tedious but straightforward to work out. Details are given in the Appendix.

In Fig. 1 we present angular distributions of the triple differential cross section $d^3\sigma/d\Omega_K d\Omega_p dp_p$ for the exclusive reaction $d(\gamma, K^+p)\Sigma^-$ (threshold 905.2 MeV). Two different versions for the elementary amplitude $\gamma n \to K^+\Sigma^-$ proposed in Ref. [2] are compared and they yield very different predictions. Applying isospin symmetry these two operators were extracted from the very sparse $\gamma p \to K^+\Sigma^0$ data, the first one containing only the Born terms while the second one also including the Δ (1670) resonance term in the s channel which helped to

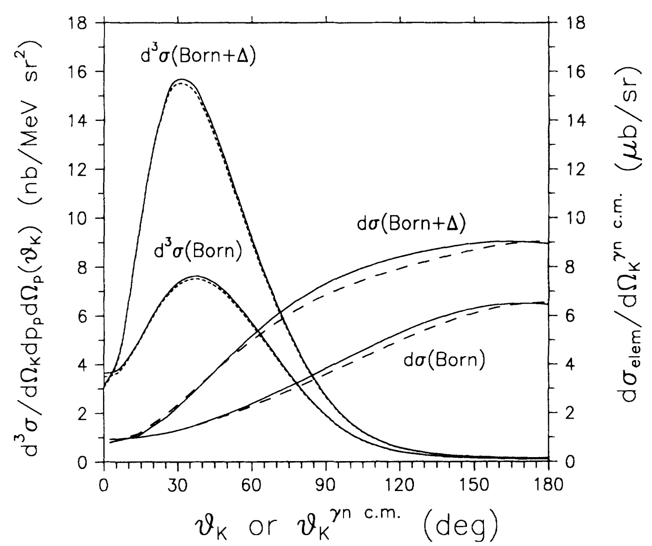

FIG. 1. Kaon angular dependence of the differential cross sections for the deuteron process $\gamma + d \to K^+ + \Sigma^- + p$ (left scale vs θ_K at bottom) and for the extracted elementary process $\gamma + n \to K^+ + \Sigma^-$ (right scale vs $\theta_K^{\gamma n\,\text{c.m.}}$ at bottom) at photon laboratory energy $E_\gamma = 1.5$ GeV, and proton kinematics: $p_p = 50$ MeV/c, $\theta_p = 30°$, $\phi_p = 180°$ are shown on the same graph for two different models of the production operator proposed by Ref. [2]. The corresponding photon energy in the photon-neutron laboratory system $E_\gamma^{\gamma n\,\text{lab}} = 1.568$ GeV. The dotted curves show the effects of distortion by the final-state Σ^-p interaction. The dashed curves are directly calculated for the free process using the same models.

improve the χ^2 fit. The final-state interaction between the Σ^- and the proton has been included via a complex potential [13] that includes the strong $\Sigma^- p \rightarrow \Lambda^0 n$ conversion channel. Since previous workers [9–12] found that final-state interaction effects in the reaction $\gamma d \rightarrow K^+ \Lambda^0 n$ can only be studied very close to threshold, we selected kinematics well away from threshold to minimize the final-state interaction effects. In principle, one should include distortions by solving the coupled channels equations of the involved baryons [12], however, at this kinematics the difference between the plane wave and distorted wave impulse approximation results does not warrant a more sophisticated calculation. Figure 1 also displays the elementary cross section for the reaction $\gamma n \rightarrow \Sigma^- K^+$ extracted from the deuteron process (g) via Eq. (9) as well as calculated directly using the free process [2]. The comparison clearly demonstrates that the contamination resulting from using the deuteron as a neutron target, such as the final-state interaction and off-shell effects, is negligible and that elementary photoproduction cross sections can be reliably extracted. Note that the relationship between $\theta_K^{\gamma n \text{c.m.}}$ and θ_K is nonlinear [see Eq. (A20)]. For example, in Figs. 1–3 $\theta_K = 30°$ approximately corresponds to $\theta_K^{\gamma n \text{c.m.}} = 68°$ while $\theta_K = 90°$ corresponds to $\theta_K^{\gamma n \text{c.m.}} = 152°$. That is, small θ_K angles cover most of the range of $\theta_K^{\gamma n \text{c.m.}}$. By measuring the peak region of the deuteron cross sections, most regions of the elementary cross sections can be extracted out using our prescription.

Figures 2 and 3 present cross sections for the K^0 photoproduction reactions (h) and (i), corresponding to the free processes (e) and (f), respectively. Again assuming isospin symmetry we employed model IV of Ref. [4] for the former process while for the latter the operators of Ref. [2] were used, just as in the reaction $\gamma n \rightarrow K^+ \Sigma^-$ in Fig. 1. Distortion by the final-state interaction is expected to be of the same order as that in Fig. 1, therefore it is

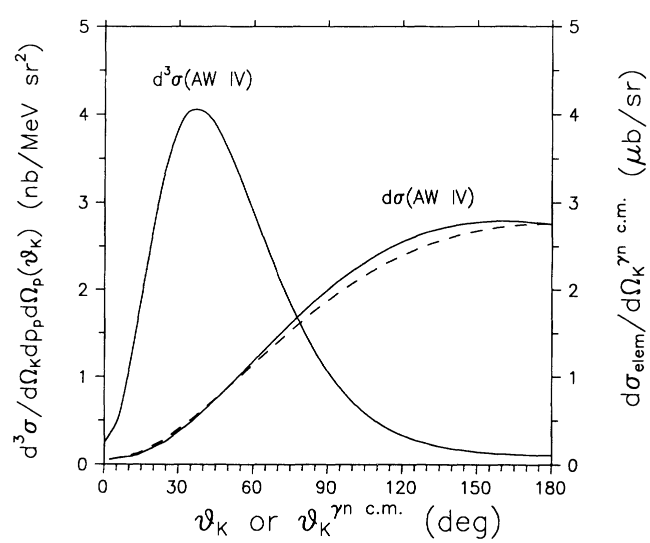

FIG. 2. Same as in Fig. 1, but for K^0 production processes involving Λ^0: $\gamma + d \rightarrow K^0 + \Lambda^0 + p$ and $\gamma + n \rightarrow K^0 + \Lambda^0$. The distortion by final-state interaction is not included. The model (AW IV) for the production operator is from Ref. [4].

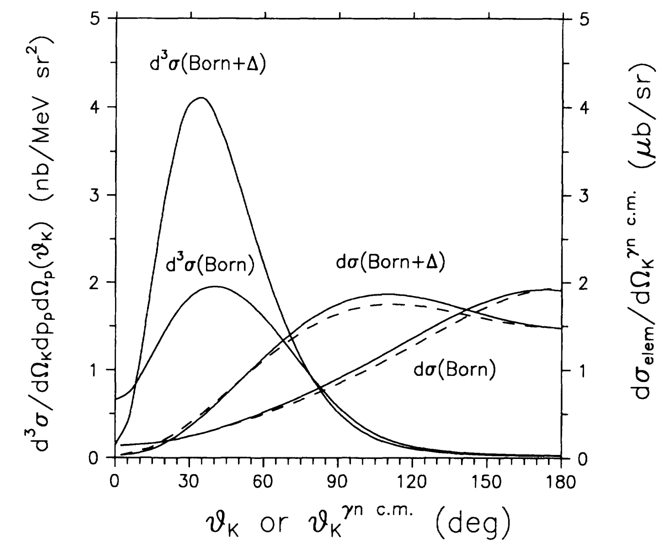

FIG. 3. Same as in Fig. 1, but for K^0 production processes involving Σ^0: $\gamma + d \rightarrow K^0 + \Sigma^0 + p$ and $\gamma + n \rightarrow K^0 + \Sigma^0$. The distortion by the final-state interaction is not included.

not included. Noteworthy is the backward peaking of the basic K^0 production cross section which may be related to the absent t-channel contribution in the Born terms. Experimental detection of neutral kaons via the $\pi^+\pi^-$ channel should not be more difficult than K^+ detection. In fact, Monte Carlo simulations of the CEBAF Large Acceptance Spectrometer indicate that near threshold the acceptance for K^0 events is much larger than for K^+ events [14]. Information on K^0 photoproduction should be supplemented with the remaining process $\gamma p \rightarrow \Sigma^+ K^0$ which may also provide good polarization measurements due to the large weak asymmetry parameter of the Σ^+. Note that the deuteron cross sections for the neutral kaon production are approximately a factor of five smaller than for charged kaon production.

In Figs. 1–3 the proton kinematics were kept constant while the cross sections were presented as a function of the kaon angle. Varying the proton angles θ_p and ϕ_p produces very little change in the deuteron exclusive cross section; however, it is very sensitive to the choice of the proton momentum. Maximum counting rates can be achieved at p_p around 50 MeV/c; at higher momenta the deuteron wave function will suppress the cross section while for lower momenta it is the phase space factor that reduces the rates.

In conclusion, we have demonstrated that the deuteron can be used to study K^0 and K^+ photoproduction from the neutron. Final-state interaction and off-shell effects are small enough so that the elementary neutron cross section can be reliably extracted. Reasonable deuteron counting rates can be expected for all but the very backward kaon angles in the photon-neutron c.m. frame. The triple differential cross sections are roughly independent of the proton angle, while its dependence on the proton momentum follows the deuteron wave function. Once experimental information about all six elementary photoproduction processes is available it should be possible to disentangle the various Born and resonance contributions and give a deeper understanding of the underlying dynamics.

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APPENDIX A: THE JACOBIAN

The extracted elementary cross section $d\sigma_{\text{elem}}$ in Eq. (9) is expressed in the deuteron laboratory frame for $\gamma+d\rightarrow K+Y+p$. A Jacobian is needed to transform this cross section into the conventional photon-neutron c.m. frame for the elementary process $\gamma+n\rightarrow K+Y$:

$$\frac{d\sigma_{\text{elem}}}{d\Omega_K}=\frac{d\sigma_{\text{elem}}}{d\Omega_K^{\gamma n\text{c.m.}}}\left|\frac{d\Omega_K^{\gamma n\text{c.m.}}}{d\Omega_K}\right| . \tag{A1}$$

The required Lorentz boost is to transform

$$P=p_\gamma+p_n=(E_\gamma+E_p,-p_x,-p_y,E_\gamma-p_z)$$

into $P'=(W,0,0,0)$, where $W=P^2$ is the total invariant energy in photon-neutron system. Therefore, we can get

$$\boldsymbol{\beta}=\frac{(-p_x,-p_y,E_\gamma-p_z)}{E_\gamma+E_p} , \quad \gamma=\frac{1}{\sqrt{1-\beta^2}} \tag{A2}$$

with the unit vector along the boost $\hat{\boldsymbol{\beta}}=\boldsymbol{\beta}/\beta=(\beta_x,\beta_y,\beta_z)$. Under this Lorentz boost, the kaon momentum vector $\mathbf{p}_K$ becomes

$$\mathbf{p}'_K=A\hat{\boldsymbol{\beta}}+\mathbf{p}_K , \tag{A3}$$

where we have defined $A\equiv(\gamma-1)\mathbf{p}_K\cdot\hat{\boldsymbol{\beta}}-\gamma\beta E_K$. It is convenient to find the polar angles of this transformed vector with respect to the deuteron laboratory frame:

$$\tan\phi'=\frac{A\beta_y+p_K\sin\theta\sin\phi}{A\beta_x+p_K\sin\theta\cos\phi} , \tag{A4}$$

$$\cos\theta'=\frac{A\beta_z+p_K\cos\theta}{p'_K} , \tag{A5}$$

where for simplicity we have suppressed the subscript K for kaon angles. The primed polar angles (θ',ϕ') are related to the desired polar angles $(\theta_K^{\gamma n\text{c.m.}},\phi_K^{\gamma n\text{c.m.}})$ by a rotation. Therefore, we can use the property that solid angle is invariant under rotation to evaluate the Jacobian by

$$\frac{d\Omega_K^{\gamma n\text{c.m.}}}{d\Omega_K}=\frac{d\Omega'_K}{d\Omega_K}=\frac{d\cos\theta'}{d\cos\theta}\frac{d\phi'}{d\phi} . \tag{A6}$$

The rest is straightward to work out. Note that p_K is constrained by the overall energy and momentum conservation:

$$E+M_d=E_K+E_Y+E_p , \quad \mathbf{p}_\gamma=\mathbf{p}_K+\mathbf{p}_Y+\mathbf{p} , \tag{A7}$$

therefore p_K, as well as E_K, is a function of (θ,ϕ). Here we give the final results:

$$\frac{d\phi'}{d\phi}=\frac{\sin\theta[(\beta_x\sin\phi-\beta_y\cos\phi)(A dp_K/d\phi-p_K dA/d\phi)+p_K(A\beta_x\cos\phi+A\beta_y\sin\phi+p_K\sin\theta)]}{(A\beta_x+p_K\sin\theta\cos\phi)^2+(A\beta_y+p_K\sin\theta\sin\phi)^2} , \tag{A8}$$

$$\frac{d\cos\theta'}{d\cos\theta}=\frac{p'_K(p_K+\beta_z dA/d\cos\theta+\cos\theta dp_K/d\cos\theta)-(A\beta_z+p_K\cos\theta)dp'_K/d\cos\theta}{(p'_K)^2} . \tag{A9}$$

Finally, we need photon energy in the photon-neutron laboratory system:

$$E_\gamma^{\gamma n\text{lab}}=\frac{W^2-M_n^2}{2M_n} \tag{A10}$$

and kaon angle in the photon-neutron c.m. system:

$$\cos\theta_K^{\gamma n\text{c.m.}}=\frac{\mathbf{p}'_K\cdot\hat{\boldsymbol{\beta}}}{p'_K} \tag{A11}$$

to complete the transformation.

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