Lambda-neutron interaction in kaon photoproduction from the deuteron

R. A. Adelseck and L. E. Wright
Physics Department, Ohio University, Athens, Ohio 45701
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The importance of hyperon-nucleon final-state interaction in kaon photoproduction from the deuteron is examined. By calculating the deuteron wave function using the Reid, Paris, or Bonn *NN* potentials, the uncertainty of this process due to the nucleonic wave function is found to be negligible. The insignificance of off-shell and relativistic effects is demonstrated by employing a completely relativistic wave function and comparing various approximations. We find the influence of the kaon production operator to be the most critical ingredient in this calculation. Final-state effects, which are included via a distorted-wave formalism, involve partial waves up to $l=3$. They produce a sharp rise of the cross section near threshold resulting in an enhancement by about a factor of 3, but diminish rapidly as the energy increases. Different ΛN potential models show variations of the effect by up to 10%.

I. INTRODUCTION

In order to obtain a comprehensive understanding of the strong interaction, it is essential that any theory reflect the underlying symmetry which is unveiled in the multiplet structure of the particles. Thus, it is indispensable to go beyond the nucleon-nucleon sector and incorporate and utilize aspects furnished by other members of the baryon multiplet, among them the lambda and sigma hyperon. To obtain a full understanding of the hyperon-nucleon as well as the hyperon-hyperon interaction is not only beneficial for the field of nuclear physics, but also sheds light on the realms of quark and particle physics.

Despite the discovery of hypernuclei thirty years ago,[1] hypernuclear physics has not gone much beyond hypernuclear spectroscopy due to lack of experimental facilities. Recent improvements in kaon and pion beams along with higher energy and duty cycle machines being constructed, such as CEBAF or the new machine in Mainz (MAMI), have led to a revival of interest in this field. Growing awareness of the importance of meson as well as quark degrees of freedom has further contributed to again attracting attention to hypernuclear physics.

Our intention in the present paper is to consider a possible experiment which is well suited for the study of lambda-neutron interaction in the continuum. This reaction has been investigated previously for photoproduction by Renard and Renard[2] and for electroproduction by Cotanch and Hsiao.[3] Currently, experimental sources of the hyperon-nucleon (*YN*) interaction, in particular of the ΛN interaction, are essentially of three kinds: (i) study of hypernuclei; (ii) low-energy direct scattering reactions, which can only involve the proton; and (iii) final-state interactions.

The extraction of the *YN* interaction from the study of hypernuclei is an elaborate task, requiring accurate knowledge of the nucleonic wave function. Due to the large freedom in the choice of and shape of the potential, it is not possible to unambiguously define all potential parameters. The process through which the hypernuclear state is formed further complicates a unique determination. Most experiments proceed via the strangeness exchange reaction (K^-,π^-) or (π^+,K^+) which involve the complex pion interaction, thereby making it difficult to extract details of the underlying potential. The photoproduction process (γ,K^+), however, provides an attractive alternative by largely eliminating any distortions in the incident channel due to the weakly interacting nature of the electromagnetic probe.

The second option, hyperon-nucleon scattering, does not presume any knowledge of nuclear structure but is hampered by the lack of hyperon beams. Moreover, the lack of neutron targets confines the analysis to Λp interactions, making it impossible to explore charge symmetry breaking effects of the involved forces. The results obtained to date by this method are quite poor and disagree with potential parameters as derived from the study of hypernuclei.[4]

The above-mentioned difficulties may be circumvented by studying hyperon-nucleon interaction in the framework of final-state interactions (FSI's). Due to different kinematical conditions, an analysis of final-state effects allows the investigation of novel regimes in the interaction not accessible to either one of the previously mentioned methods. In particular, FSI is the only way to examine the hyperon-neutron interaction by itself.

In this paper we employ the photoproduction of a positively charged kaon off the deuteron system to examine final-state effects caused by the lambda-neutron interaction. We investigate the sensitivity of the inclusive reaction $^2\mathrm{H}(\gamma,K^+)\Lambda n$, as well as of the exclusive reaction $^2\mathrm{H}(\gamma,K^+\Lambda)n$. We also test the assumption by Renard and Renard[2] that corrections to the relative Λn *s* state only are sufficient to describe the final-state interaction.

The interaction of the photon and of the K^+ meson are reasonably well understood and comparatively weak, justifying first-order theoretical treatment. Experimentally, however, the weakness of the interaction results in low counting rates and small cross sections. The advantage of the deuteron as a target nucleus lies in the theoretically rather well-known nucleonic wave function. In the process under consideration it serves as a neutron source and simultaneously provides the proton to be converted into a lambda via $^1H(\gamma,K^+)\Lambda$. Thus, there are no residual nucleons which would screen the effect of the Λn interaction.

The choice of a photon and a deuteron in the initial state minimizes any uncertainties in the incident channel. Furthermore, in this paper we neglect the final-state interaction of the K^+ meson with the neutron due to the weakness of the K^+-nucleon interaction. This small perturbation, however, could be included in future studies.

In Sec. II we briefly discuss the properties of the deuteron system. We display the uncertainties introduced by the wave function by comparing results obtained under the assumption of a Reid,[5] Paris,[6] or Bonn[7] nucleon-nucleon potential. The significance of relativistic effects is examined by using a relativistic model proposed by Gross.[8]

The model for the photoproduction operator is based on a phenomenological analysis of the elementary $^1H(\gamma,K^+)\Lambda$ process. We give a brief overview of the elementary production operator in the third section of this paper. A complete description can be found elsewhere.[9]

In Sec. IV we describe the application of the basic operator to the deuteron system in the spirit of an impulse approximation. Relativistic and off-shell effects are investigated by extending the operator to the regime of relativistic wave functions and testing various approximations. In order to incorporate the Λn final-state interaction into the process, we utilize a distorted-wave formalism. A description of this procedure as well as the results are presented in Sec. V. We conclude the study with a summary and a few final remarks in Sec. VI.

II. THE DEUTERON

Due to the fact that the deuteron is a two-body system, it is possible to separate the motion of the center of momentum from the relative motion in a well-defined manner. This enables us to rigorously write the wave equation, involving only easily controllable approximations to the assumed interaction. Thereby we avoid the difficulty encountered in the treatment of many-body problems ($A \geq 4$) where approximations to the wave equation itself need to be made, or where the resulting wave function may contain spurious excitations of the center of momentum.

Even though in a Schrödinger picture the only uncertainty in the two-body problem lies in the underlying nucleon-nucleon potential, there exists considerable doubt regarding the question of a relativistic wave equation. Several attempts have been made to construct a relativistic two-body equation,[10,11] but no unique procedure has been found.[12,13] The model used in this work follows a prescription suggested by Gross.[8,14,15]

The general form of the deuteron wave function in momentum space is shown in Eqs. (1a) and (1b), and Eqs. (2a) and (2b) represent the corresponding coordinate space expression.

$$\Psi_{rs}^{+}=u(\hat{\mathbf{p}})\langle\hat{\mathbf{p}}|(01)1M\rangle-w(\hat{\mathbf{p}})\langle\hat{\mathbf{p}}|(21)1M\rangle , \quad (1a)$$

$$\Psi_{rs}^{-}=v_s(\hat{\mathbf{p}})\langle\hat{\mathbf{p}}|(10)1M\rangle+v_t(\hat{\mathbf{p}})\langle\hat{\mathbf{p}}|(11)1M\rangle ; \quad (1b)$$

$$\Psi_{rs}^{+}(\mathbf{r})=\frac{\tilde{u}(r)}{r}\langle\hat{\mathbf{r}}|(01)1M\rangle+\frac{\tilde{w}(r)}{r}\langle\hat{\mathbf{r}}|(21)1M\rangle , \quad (2a)$$

$$\Psi_{rs}^{-}(\mathbf{r})=i\frac{\tilde{v}_s(r)}{r}\langle\hat{\mathbf{r}}|(10)1M\rangle+i\frac{\tilde{v}_t(r)}{r}\langle\hat{\mathbf{r}}|(11)1M\rangle . \quad (2b)$$

The notation $|(lS)1M\rangle$ indicates coupling of the relative motion between proton and neutron with angular momentum l and total spin S to the deuteron $J=1$ and z component $M=0,\pm1$; according to standard notation, the coordinate (momentum-) space representation is denoted by $\langle\hat{\mathbf{r}}|(\langle\hat{\mathbf{p}}|)$. The S- and D-state wave function are conventionally represented by u and w, while v_s and v_t stand for the singlet and triplet P-state wave function, respectively. The presence of P-state components in the deuteron wave function is a purely relativistic effect and is not predicted in any nonrelativistic theory. Details on the relativistic deuteron wave function, including the shape and size of the P state, may be found in Ref. 7.

To obtain reasonable counting rates for the photoproduction reaction requires choosing the kinematical situation so that the proton and the neutron have rather low relative momentum. Even though a large relative momentum might, under certain conditions, be able to enhance the photoproduction process by reducing the momentum mismatch in the basic operator, the overall cross section will still be greatly suppressed due to the strong decrease of the deuteron wave function for high relative momenta. Thus, in order for the reaction $^2H(\gamma,K^+)\Lambda n$ or $^2H(\gamma,K^+\Lambda)n$ to yield practical counting rates, we need to choose low relative momentum states for the two nucleons. Due to this pragmatic condition, the process is completely dominated by the S-state wave function u. Hence, we can be confident that the initial channel is sufficiently well described if there are only minor deviations in the description of the deuteron's S

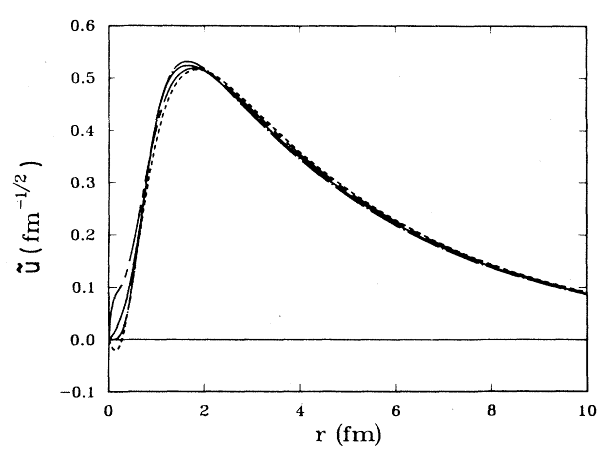

FIG. 1. Comparison of the deuteron S wave as predicted by Gross (— — —), Reid (—·—·—·), the Paris group (——), and the Bonn group (- - -).

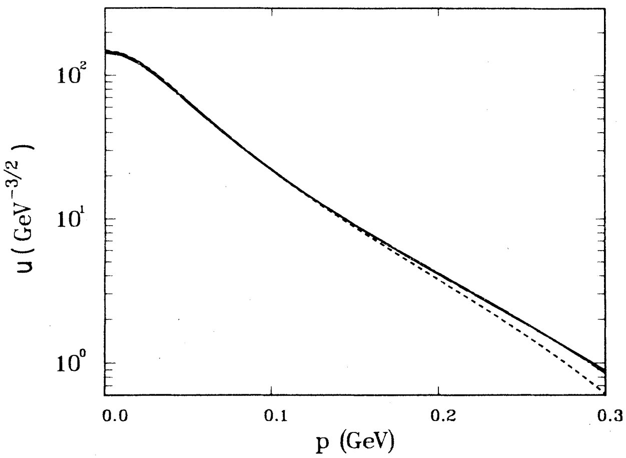

FIG. 2. Low-momentum behavior of the deuteron wave function. (Same notation as in Fig. 1.)

state when employing different NN potential models. A well-defined nucleonic wave function for the initial state is essential to guarantee that final-state effects are not hidden by our insufficient knowledge of the system. In Figs. 1 and 2 we give a comparison of the dominant S wave of the deuteron as calculated in a relativistic framework by Gross,[8] and nonrelativistically based on NN potential models by Reid,[5] the Paris group,[6] and the Bonn group.[7] The coordinate space representation (Fig. 1) shows minute deviations at short distances which correspond to high-momentum components in the wave function (Fig. 2). Since in this regime the wave function is smaller by an order of magnitude as compared to its peak value, uncertainties due to our inaccurate knowledge of the NN interaction are negligible for the kinematical domain under consideration.

III. THE BASIC OPERATOR

First attempts in the formulation of an invariant kaon photoproduction operator were made by Thom[16] twenty years ago. Using a diagrammatic technique, he developed an operator whose coupling constants were obtained by a least-squares fit to the available $^1\mathrm{H}(\gamma,K^+)\Lambda$ data. Since that time many new models[17–19] have emerged, improving upon his result. A long-standing puzzle among all these phenomenological models has been the disagreement between the coupling constants, in particular the $K\Lambda N$ constant, obtained from this electromagnetic process as compared to the value obtained via hadronic probes[20] or from quark model predictions.[21]

In a recent study,[9] we extended the analysis of the photoproduction process to include the data set from the electroproduction reaction $^1\mathrm{H}(e,e'K^+)\Lambda$ as well. This provided additional constraints on the question of which resonant terms were to be included in the elementary $(\gamma\{\gamma_v\},K^+)$ production operator. We were able to obtain an excellent description of the electroproduction process with the $K\Lambda N$ coupling constant approaching values comparable to predictions from the hadronic sector and, in particular, were able to reconfirm the charge radius of the K^+ which had been previously measured. Our new fit to the photoproduction data also produced coupling constants more in accord with hadronic analyses, but the resulting χ^2 was rather large. After various tests, we found evidence that the difficulty in fitting the photoproduction data is not so much a problem of the operator, but of the quality and consistency of the available data points. Experiments based on electron scattering instead of real photon beams provide more accurate and reliable data, thus having a higher predicative power. Improved measurements of the photoproduction process are desirable to compare the importance of different production mechanisms for real and virtual photons.

We derived the operator based on the assumption of a one-photon exchange mechanism. The best fit was obtained when we included— besides the first-order proton-, kaon-, and lambda-exchange diagrams— two s-channel nucleon resonance, one u-channel hyperon resonance, and two t-channel kaon resonances. Details regarding the vertex factors, form factors, and coupling constants can be found in Ref. 9.

IV. PHOTOPRODUCTION OFF THE DEUTERON

The principal difference between the pion and kaon production from the deuteron system lies in the absence of the Δ resonance in the latter case. Since the $T=J=\frac{3}{2}$ state cannot be excited, the necessity of taking the complex N-Δ interaction into consideration is eliminated. Furthermore, due to the neutron and the lambda being distinguishable particles, we do not face the problem of antisymmetrizing the baryonic final state.

Under the assumption that the incoming photon interacts with the proton only, we are able to describe the production process in the framework of the spectator nucleon model.[22] Without final-state interaction, the neutron as the spectator nucleon remains unaffected during the process and is subsequently being detected. Thus, the on-shell structure of the neutron requires the proton to propagate as an off-shell Dirac particle, as illustrated in Fig. 3. By using the conventional decomposition of a Dirac propagator, shown in Eq. (3), we now connect the off-shell behavior of the proton to the v-spinor components. For comparison the propagator of a particle on its positive-energy mass shell is given in Eq. (4). The notation follows the convention of Bjorken and Drell.[23]

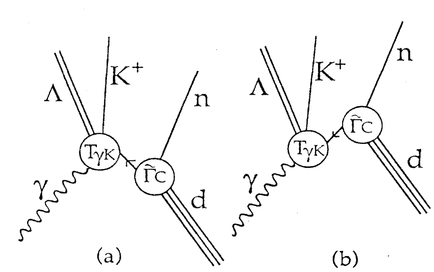

FIG. 3. Time-ordered diagrams for the reaction $d(\gamma,K^+\Lambda)n$. The proton propagates forward (a) or backwards (b) in time.

$$\frac{\not p + m}{p^2 - m^2} = \frac{m}{E} \sum_s \left[\frac{u(\mathbf{p},s)\bar{u}(\mathbf{p},s)}{p^0 - E} + \frac{v(-\mathbf{p},s)\bar{v}(-\mathbf{p},s)}{p^0 + E} \right] , \tag{3}$$

$$\frac{\not p + m}{2E} = \frac{m}{E} \sum_s u(\mathbf{p},s)\bar{u}(\mathbf{p},s) . \tag{4}$$

The v-spinor components are, in turn, related to the P-wave contributions in the deuteron wave function, as can be seen from Eqs. (1b) and (2b), thus establishing a link between the off-shell behavior of the proton and its "antiparticle" components.

To obtain a complete description of the photoproduction process, it is furthermore necessary to incorporate the additional degree of freedom, introduced by the arbitrary relationship between the proton's energy and momentum, into the basic kaon production operator (Sec. III). Since we employ a diagrammatic technique, this can easily be achieved by using the following identities in the derivation of the basic operator:

$$\not p_p = (p_0, \mathbf{p}) = (E_p, \mathbf{p}) + (p_0 - E_p, \mathbf{0}) , \tag{5}$$

$$\not p_p u(\mathbf{p}) = M_p u(\mathbf{p}) + (p_0 - E_p)\gamma_0 u(\mathbf{p}) , \tag{6a}$$

$$\not p_p v(-\mathbf{p}) = M_p v(-\mathbf{p}) + (p_0 + E_p)\gamma_0 v(-\mathbf{p}) , \tag{6b}$$

where p_0 represents an arbitrary proton energy, and $E_p^2 = \mathbf{p}^2 + M_p^2$ is the on-shell energy. The application of Eqs. (5) and (6) significantly complicates the operator. However, the so-derived operator together with the relativistic deuteron wave function provides a completely relativistic description of the kaon photoproduction from the deuteron.

A particular advantage of this procedure is its simplicity in controlling various approximations. By rejecting the v-spinor contribution [Eq. (6b)], the P-state components in the deuteron are neglected and the relativistic nuclear wave function reduces to its nonrelativistic counterpart, still accounting to some extent for possible off-shell effects. If, in addition to this approximation, p_0 is set equal to E_p, we recover the conventional impulse approximation.

As was to be expected, relativisitic and off-shell corrections are found to be important only for high-momentum components of the spectator neutron. In such a situation, momentum conservation at the deuteron vertex requires a large relative proton-neutron momentum, i.e., the reaction takes place far into the tail of the deuteron's momentum-space function. This leads to unreasonably low counting rates, since the cross section in the spectator nucleon model is proportional to the square of the nucleonic wave function. To obtain measurable cross sections, it is necessary to stay in a kinematical region close to the threshold for a given kaon momentum and solid angle. The threshold for $\gamma d \rightarrow K^+ \Lambda n$ is 794.03 MeV.

Figures 4 and 5 demonstrate the difference between the impulse approximation and the full calculation. The notations $d^2\sigma$ and $d^3\sigma$, respectively, denote

$$d^2\sigma \equiv \frac{d^2\sigma}{dP_K d\Omega_K}$$

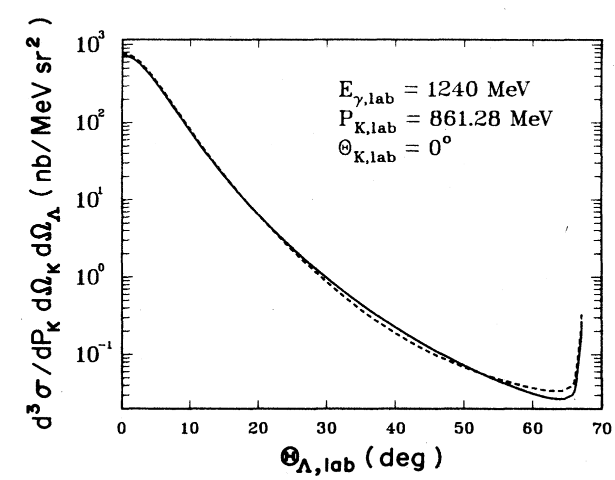

FIG. 4. Illustration of off-shell effects in $d(\gamma,K^+\Lambda)n$. The solid curve is an impulse approximation and the dashed curve is a full calculation.

and

$$d^3\sigma \equiv \frac{d^3\sigma}{dP_K d\Omega_K d\Omega_\Lambda} ,$$

where P_K is the magnitude of the kaon's three-momentum.

In the coincidence cross section $^2H(\gamma,K^+\Lambda)n$, minor deviations can be seen at large lambda angles where the cross section has already dropped by about three orders of magnitude. The discrepancy is more prominent in the $^2H(\gamma,K^+)\Lambda n$ process, where its maximum occurs near the peak of the cross section. However, corrections are still less than 10%. The deuteron wave function used in the full calculation is the one suggested by Gross, while the one employed in the impulse approximation has been calculated from the Paris potential.

We found the largest uncertainty in the photoproduc-

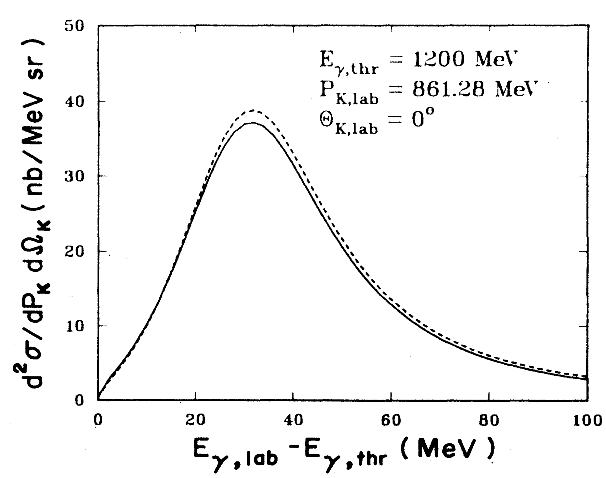

FIG. 5. Same as Fig. 4.

tion process to be introduced by the basic operator. Depending on the particular choice of the operator (inclusion of different resonances, uncertainly in coupling constants) we found deviations in the cross section of up to 35%. The photoproduction operator used to calculate the figures in this paper is given by the best fit as presented in Ref. 9. As an aside, we note that our fits to the elementary electroproduction data do not allow a variation of the kaon form factor as considered by Cotanch and Hsiao.[3]

We are confident that apart from the elementary operator, the kaon photoproduction process from the deuteron is adequately described by the impulse approximation and that relativistic and off-shell corrections do not play a significant role in the kinematical regime under consideration.

V. LAMBDA-NEUTRON FINAL-STATE INTERACTION

In the formalism outlined in Sec. III we not only assumed the neutron to be a spectator to the production process, we also neglected any perturbation of the neutron wave function due to interaction with the produced particles.

The final state of the process under consideration contains three distinct particles involving three substantially different types of two-body interactions. The $K\Lambda$ interaction, which certainly provides an important contribution, has already been taken care of through the phenomenological approach by which we construct the basic operator. Corrections to the cross sections can, therefore, only come from effects of the interaction between the neutron and the kaon or the lambda. Supposing that modifications caused by the KN interaction[2,24] are insignificant compared to the remaining final-state effects and to the uncertainties in the particular choice of the basic production operator, we disregard its contribution and consider only the effect of the Λn interaction. A three-body interaction is in principle conceivable, but so far no clear evidence for such a force has been found.

The primary purpose of this study is to investigate to what extent the reaction $\gamma d \rightarrow K^+ \Lambda n$ can be used as a tool in studying the hyperon-nucleon interaction. To answer this question, we need to focus our attention on two main points. Firstly, is there a significant contribution coming from the final-state interaction and secondly, is it possible to distinguish between different potential models. The question by how much the remaining ingredients (production operator, deuteron wave function) in this process influence or screen the final-state effect has already been discussed in the preceding sections.

Since we are interested in the ability of this reaction to differentiate between various potential models, we choose two representations for the lambda-nucleon potential with quite different functional behavior and potential parameters. For the present purpose it is sufficient to use models with a rather simple analytic form, allowing for a different strength and shape in the spin-singlet and triplet state of the Λn system. If this reaction proves to be useful as a probe of Λn interaction, more sophisticated models[4,25] may be implemented.

One of the first potentials developed was the one by Bhaduri *et al.*[26] who suggested a Yakawa-type potential with a cutoff at short distances. We chose the parameters of set 1 in their paper, corresponding to a singlet scattering length of $a_s = -2.46$ fm and a singlet effective range of $r_s = 3.87$ fm; the triplet parameters are $a_t = -2.07$ fm and $r_t = 4.50$ fm. The other model considered in the current paper is the more recent Verma-Sural[27] potential, which assumes a double-Gaussian shape. The potential parameters of their set 3 correspond to the following low-energy scattering parameters: $a_s = -2.29$ fm, $r_s = 3.14$ fm, $a_t = -1.77$ fm, and $r_t = 3.25$ fm. The dominant features of these two models are the short distance repulsion of the Verma-Sural potential and the relatively long range of the Yukawa-type potential.

To incorporate the final-state interaction into the production process, we employ a nonrelativistic distorted wave formalism, which is justified due to the fact that neither relativistic nor off-shell effects play an important role in the description of the given process (see Sec. III). The distorted-wave function for the relative Λ-n motion is obtained by numerically solving the Schrödinger equation for the two-body system. Having calculated the distorted-wave function, we insert a complete system $(\int |\Lambda' n'\rangle\langle \Lambda' n'|)$ of plane-wave states between the distorted state $(\langle \Lambda n|)$ and the production operator T:

$$M_{fi} = \left\langle \Lambda n \left| \int \right| \Lambda' n' \right\rangle \langle \Lambda' n' | \langle K | T | \gamma d \rangle \ .$$

The projection of the distorted-wave function onto the plane-wave states as well as one of the integrations involved in the complete system are carried out numerically. Due to our particular choice of the operator, it is convenient to express the integration regarding the complete system in momentum space rather than in coordinate space. Since one of the momentum-space integrals needs to be integrated numerically up to infinity, we truncate it at some large value where the cross section has already decreased by several orders of magnitude.

Besides testing the sensitivity to the underlying potential model, we also examined the dependence of the final-state effect on the number of partial waves included in the distorted-wave calculation. Renard and Renard[2] in an earlier study concluded that corrections to the relative s-state wave function provided an adequate description of the final-state interaction. Our analysis, however, shows that s-state corrections, depending on the kinematical region, account for only 50% of the total effect. For an accurate description of the interaction, we find it necessary to include the lowest four partial waves, i.e., up to $l = 3$.

Figures 6–8 demonstrate the size of the final-state effect. A comparison of Figs. 6 and 7 shows that corrections due to the lambda-neutron interaction are not at all negligible in the reaction $^2\mathrm{H}(\gamma, K^+)\Lambda n$, while causing an effect of less than 8% in the exclusive process $^2\mathrm{H}(\gamma, K^+\Lambda)n$. Even though these two figures have been calculated at different energies, this difference between the inclusive and exclusive reaction is a general result which holds at any energy. Thus, in kaon photoproduction from the deuteron, final-state interaction effects can

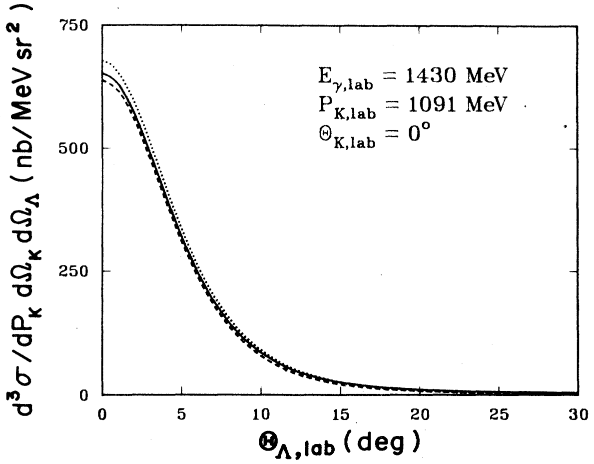

FIG. 6. Comparison of $d^3\sigma$ without ($\cdots$) and with Λ-n interaction ($l=0$: — — —, $l=0$–3: ——), using the potential by Verma and Sural.

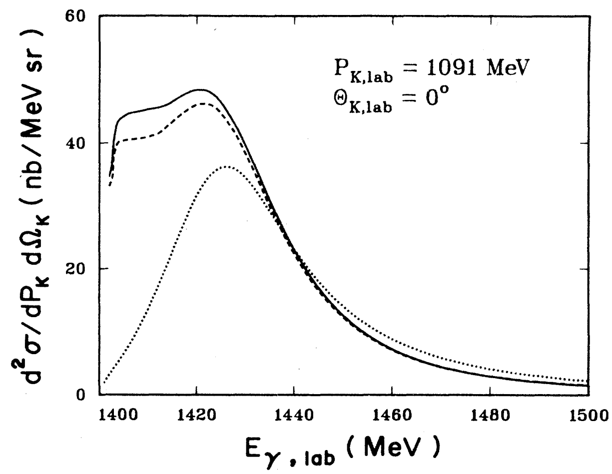

FIG. 8. Comparison of $d^2\sigma$ using the ΛN potential by Bhaduri *et al.* (— — —), the potential by Verma and Sural (——), and the plane-wave approximation ($\cdots$).

be observed by detecting only the kaon. Figure 7 also displays the typical behavior of the final-state corrections in this process. The Λn interaction causes the cross section to rise sharply at threshold, increasing the cross section by about a factor of 3. This distinct enhancement, however, is strongly concentrated in a very narrow region of about 30–40 MeV above threshold. Beyond that limit, the cross section drops slightly below the undistorted result and for all practical purposes remains indistinguishable from the interaction-free case.

As can be seen from Fig. 7, the s-state contribution alone only gives about 60% of the final-state interaction effect. We find that three to four partial waves are needed to evaluate the final state completely. Due to the concentration of the Λn interaction near threshold, we are not able to see effects from lambda-sigma conversion which occurs at about 80 MeV above the lambda threshold.

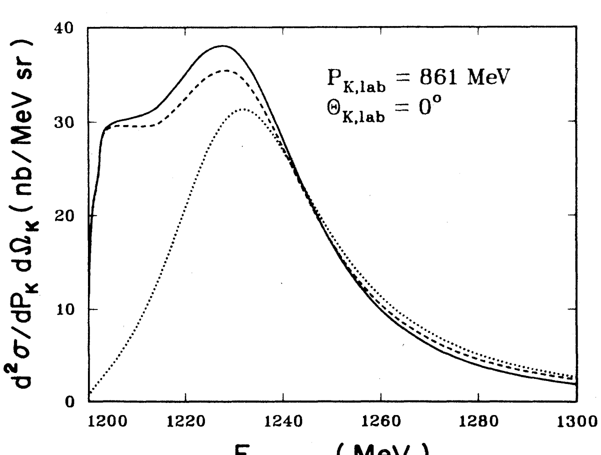

FIG. 7. Same as Fig. 6, but for $D^2\sigma$.

The sensitivity of the cross section to the choice of the underlying ΛN potential is illustrated in Fig. 8. We find the shape of the curves to be almost independent of the particular model. The magnitude of the final-state corrections due to the different interaction models shows variations on the order of 10%. This, together with the very similar shape of the curves, requires highly accurate measurements in order to be able to distinguish among different potential models.

The kaon laboratory angle in Figs. 6–8 has been chosen to be 0° to achieve maximum cross sections. Moving the kaon away from the beam axis results in a reduction of the final-state effect as well as an overall decrease of the cross section, but the general behavior remains the same.

VI. CONCLUSION

The purpose of this paper was the investigation of the reaction $\gamma d \to K^+ \Lambda n$ as a means of probing the lambda-neutron interaction. All currently existing ΛN potential models are based on either the study of hypernuclei or on Λp scattering experiments. These reactions, however, produce unreliable and somewhat inconsistent results. Therefore, an independent approach by which these models can be tested and compared is desirable. Due to the different kinematical regime, final-state interactions are able to investigate parts of the interaction not accessible to either one of the above-mentioned methods. In addition, they provide an excellent opportunity for exploring the lambda-neutron interaction which complements the existing data on lambda-proton interaction. A comparison of these two types of interactions will then enable us to deduce information on possible charge symmetry breaking effects.

The kaon photoproduction process from the deuteron provides a very attractive mechanism by which to study final-state effects. A reliable nucleonic wave function combined with a well-understood electronic probe and the weakly interacting K^+ meson establish a firm base from which dependable conclusions about any final-state corrections can be drawn. The only drawback is a low counting rate arising from the rather weak electromagnetic interaction. To obtain reasonable cross sections, the kaon needs to be emitted along the beam axis and measurements have to be taken in a very narrow region just above threshold for the chosen kinematics.

Given the deuteron wave function and the basic kaon photoproduction operator, we calculated the disintegration of the deuteron with associated lambda production within the framework of the spectator nucleon model. Corrections due to lambda-neutron final-state interaction were included via a distorted-wave formalism. The sensitivity of this process to relativistic effects, off-shell behavior, production mechanism, and underlying lambda-nucleon potential was examined.

By employing different NN potentials, we found only a very weak dependence of the particular nucleonic wave functions. Uncertainties arising from possible relativistic effects or from the off-shell structure of the proton proved to be insignificant within the kinematical region under consideration. The largest uncertainty was introduced by our insufficient knowledge of the basic photoproduction mechanism.

Final-state effects dominate the cross section near threshold. They produce an abrupt rise in the cross section right at the threshold value leading to an enhancement of up to a factor of 3. Increasing the energy by as much as 30–40 MeV, however, causes this effect to vanish. Thus, final-state corrections are essential only near threshold, but can be neglected at higher energies.

Contrary to the conclusion of Renard and Renard,[2] we found that inclusion of s-state corrections only provide an insufficient description of the final-state interaction. Distortions of the first four partial waves were necessary to obtain stable results. The sensitivity of the final-state interaction to the underlying lambda-nucleon potential was found to be fairly weak. Shape as well as size of the final-state effect is almost independent of the assumed interaction. Highly accurate measurements are needed in order to draw any dependable conclusions on details of the lambda-neutron potential. Due to the low counting rates in this process, this task requires great effort and refined instrumentation. Nevertheless, we suggest that measurements from the deuteron provide an attractive alternative for studying the ΛN, in particular the Λn system.

A possible alternative for the investigation of the Λn interaction would be to use kaon factories to analyze the related process $K^- d \to \gamma \Lambda n$.[28] Even though the initial state is more complex than in the reaction studied in this paper, the final state displays a clean lambda-neutron interaction. Also, the reduced momentum mismatch in this process favors creation of the Λ-n system in a relative s-state.

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[1]M. Danrsz and J. Pniewski, Philos. Mag. **44**, 348 (1953).
[2]F. M. Renard and Y. Renard, Phys. Lettt. **24B**, 159 (1967); Nucl. Phys. **B2**, 389 (1967).
[3]S. R. Contanch and S. Hsiao, Nucl. Phys. **A450**, 419c (1986).
[4]C. Daskaloyannis, M. Grypeos, and H. Nassena, Phys. Rev. C **26**, 702 (1982).
[5]Roderick V. Reid, Jr., Ann. Phys. (N.Y.) **50**, 411 (1968).
[6]M. Lacombe *et al.*, Phys. Rev. C **21**, 861 (1980).
[7]R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).
[8]Franz Gross, Phys. Rev. C **10**, 223 (1974).
[9]R. A. Adelseck and L. E. Wright, Phys. Rev. C **38**, 1965 (1988); R. A. Adelseck, Ph.D. dissertation, Ohio University, 1988.
[10]E. E. Salpeter and H. A. Bethe, Phys. Rev. **84**, 1232 (1951).
[11]R. Blankenbecler and R. Sugar, Phys. Rev. **142**, 1051 (1966).
[12]R. J. Yaes, Phys. Rev. D **3**, 3086 (1971).
[13]R. M. Woloshyn and A. D. Jackson, Nucl. Phys. **B64**, 269, (1973).
[14]J. Hornstein and F. Gross, Phys. Lett. **47B**, 205 (1973).
[15]W. W. Buck and F. Gross, Phys. Rev. D **20**, 2361 (1979).
[16]H. Thom, Phys. Rev. **151**, 1322 (1966).
[17]T. K. Kuo, Phys. Rev. **129**, 2264 (1963).
[18]R. A. Adelseck, C. Bennhold, and L. E. Wright, Phys. Rev. C **32**, 1681 (1985).
[19]A. S. Rosenthal *et al.*, Ann. Phys. (N.Y.) **184**, 33 (1988).
[20]Joseph Cohen, Phys. Rev. C **37**, 187 (1988).
[21]M. Bozoian *et al.*, Phys. Lett. **122B**, 138 (1983).
[22]J. M. Laget, Phys. Rev. **69**, 1 (1980).
[23]J. D. Bjorken and S. D. Drell, *Relativistic Quantum Mechanics* (McGraw-Hill, New York, 1964).
[24]Carl B. Dover and George E. Walker, Phys. Rep. **89**, 1 (1982).
[25]A. Faessler and U. Straub, Phys. Lett. **183B**, 10 (1987).
[26]R. K. Bhaduri, Y. Nogami, and W. van Dijk, Phys. Rev. **155**, 1671 (1960).
[27]S. P. Verma and D. P. Sural, Phys. Rev. C **22**, 229 (1980).
[28]R. L. Workman, Ph.D. thesis, University of British Columbia, 1987.