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Radiative capture of kaons by the deuteron and the Λ-n scattering lengths

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We have calculated the photon spectrum for the reaction $K^-d \to \Lambda n\gamma$ in order to consider the feasibility of its use in a determination of the Λ-n singlet and triplet scattering lengths. We have used realistic deuteron wave functions obtained from the Bonn potential, a Λ-n scattering wave function parametrized in terms of a scattering length and effective range, and an effective interaction obtained from an earlier calculation of $Kp \to \Lambda\gamma$ including momentum dependence through $O(p/m)$. We find that the photon spectrum is sensitive to the choice of Λ-n scattering lengths, yet relatively insensitive to the choice of deuteron wave functions, to momentum dependence in the transition operator, and to the contributions from other intermediate channels involving $\Sigma N \to \Lambda n$ conversions.

I. INTRODUCTION

The reaction $K^-d \to \Lambda n\gamma$ is attracting renewed interest, mainly because of the possibility of deducing a value for the Λ-n scattering lengths from the resulting photon spectrum. This reaction is the strange analog of $\pi^-d \to nn\gamma$. The latter nonstrange reaction has been utilized[1] in an accurate determination of the s-wave n-n scattering length.

Early theoretical calculations of $\pi^-d \to nn\gamma$, for at-rest pion capture, found[2] the high-energy end of the photon spectrum to be sensitive to the final-state n-n interaction. This sensitivity is understood if one realizes that the high-energy limit of the photon spectrum corresponds to the geometry in which both neutrons are emitted antiparallel to the photon and with zero relative momentum. An added bonus in this reaction is that, in the final state, the γ-n interaction is negligible in comparison to the n-n interaction. Thus, this calculation is relatively free of theoretical uncertainty when compared with calculations of reactions having three strongly interacting particles in the final state.

The use of the reaction $K^-d \to \Lambda n\gamma$ in a determination of the Λ-n scattering lengths is more beset by difficulty. Unlike the $\pi^-d \to nn\gamma$ reaction,[2] the $K^-d \to \Lambda n\gamma$ process is strongly suppressed[3] relative to final states containing three strongly interacting particles. Thus, sufficient statistics will be more difficult to obtain. In addition, background photons from the π^0 decay in the $K^-d \to \Lambda n\pi^0$ reaction may overwhelm a large part of the $K^-d \to \Lambda n\gamma$ photon spectrum. However, preliminary indications[4] suggest that these extraneous photons can be experimentally vetoed in the region of the photon spectrum most sensitive to the Λ-n final-state interaction. These experimental difficulties have been confronted by an experimental group[5] working at Brookhaven, apparently with some success. The reaction has been seen, and when analyzed using the theory described herein, gives some indication of nonzero Λ-n scattering lengths.

Apart from some early considerations[6] of $K^-d \to \Lambda n\gamma$ and $\gamma d \to \Lambda nK^+$, only two detailed calculations of the former reaction exist. The first[7] was carried out in analogy with the $\pi^-d \to nn\gamma$ calculation of Ref. 8. The radiative capture operator was taken to be momentum independent and of the form $\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}$, where $\boldsymbol{\sigma}$ operates on the proton spinor and $\boldsymbol{\epsilon}$ is the photon polarization vector. A Reid soft-core deuteron was used, and the influence of short-range effects on the final-state wave function was examined using the model of Picker, Redish, and Stephenson.[9] An interesting outcome of this calculation was the discovery of a region of the photon spectrum which was very sensitive to the Λ-n final-state interaction. This region extends from approximately 285 to 293 MeV, the endpoint of the photon energy spectrum, for Λ-n scattering lengths between -1 and -3 fm. Although this calculation was not published, it laid the foundation for future work.

A second calculation which appeared five years later[10] considered the capture reactions $K^-d \to Yn\gamma$ for the YN states Λn, $\Sigma^0 n$, and $\Sigma^- p$, and allowed for conversion between the various YN states. While relations were given for a full calculation of $K^-d \to \Lambda n\gamma$, only the Hulthen S-state deuteron was used in generating numerical results. More importantly, the calculated results concentrated on variations of the photon spectrum peak, which exists near 280 MeV, for different sets of scattering parameters describing the $K^-N \to Y\gamma$ and $YN \to Y'N'$ processes. As mentioned, the sensitive region is actually nearer to the endpoint of the spectrum.

We have calculated the photon spectrum for the reaction $K^-d \to \Lambda n\gamma$, following and extending the treatments of Refs. 7 and 10. In Sec. II we describe the formalism used and in Sec. III we discuss the sensitivity of the calculation to the various ingredients of the calculation and give results and conclusions.

II. FORMALISM

The amplitude for this reaction is of the form

$$M = \sum_{j=1}^{3} \int d^3r\, \Psi_j^{(f)\dagger}(r)\hat{T}_j \Psi^{(i)}(r) , \tag{1}$$

wherein the superscripts (i) and (f) label the initial and final states, respectively. The subscript j labels the contributions from the three final-state interaction mechanisms. The $j=1$ contribution to M results from a radiative kaon capture reaction[11,12] of the form $K^- p \to \Lambda\gamma$, and $\Lambda n \to \Lambda n$ scattering in the final state. The $j=2$ and $j=3$ contributions result from the $K^- p \to \Sigma^0 \gamma$ and $K^- n \to \Sigma^- \gamma$ capture reactions, and the respective conversion reactions, $\Sigma^0 n \to \Lambda n$ and $\Sigma^- p \to \Lambda n$, in the final state. The initial-state wave function $\Psi^{(i)}$ was taken as a product of the kaon and deuteron wave functions,

$$\Psi^{(i)} = \phi_K(0)\Phi_d(\mathbf{r}) \ , \tag{2}$$

where $\mathbf{r}$ is the relative coordinate $\mathbf{r}_p - \mathbf{r}_n$. For $\Phi_d(\mathbf{r})$ we have utilized the dueteron wave functions produced by the full and one-boson-exchange Bonn[13] potentials, keeping both S and D states, and for comparison purposes, the Hulthen wave function used in Ref. 10. We have assumed that the kaons are captured mainly[14] from S-wave atomic orbitals and, as in the two previously described calculations,[7,10] have approximated the kaonic wave function by a constant in Eq. (1). It should be mentioned that the derivation of a precise kaonic-atom wave function, even given knowledge of the exact orbital from which capture takes place, is a difficult problem. The difficulty lies in the large number of channels to which $K^- p$ can couple, and is manifested in the notoriously difficult to fit $K^- p$ atom $1s$ level energy shift. Considerable progress has, however, recently been made toward an understanding of this problem.[15]

The transition operators, $\hat{T}_j$, in Eq. (1) are given in the simplest approximation by

$$\hat{T}_1 = F_1 e^{-i\mathbf{k}\cdot\mathbf{r}_p}\delta(\mathbf{r}_p - \mathbf{r}_Y)\delta(\mathbf{r}_n - \mathbf{r}_N)\boldsymbol{\sigma}_p \cdot \boldsymbol{\epsilon} \ , \tag{3}$$

$$\hat{T}_2 = F_2 e^{-i\mathbf{k}\cdot\mathbf{r}_p}\delta(\mathbf{r}_p - \mathbf{r}_Y)\delta(\mathbf{r}_n - \mathbf{r}_N)\boldsymbol{\sigma}_p \cdot \boldsymbol{\epsilon} \ , \tag{4}$$

$$\hat{T}_3 = F_3 e^{-i\mathbf{k}\cdot\mathbf{r}_n}\delta(\mathbf{r}_n - \mathbf{r}_Y)\delta(\mathbf{r}_p - \mathbf{r}_N)\boldsymbol{\sigma}_n \cdot \boldsymbol{\epsilon} \ , \tag{5}$$

where $\boldsymbol{\sigma}_p$ ($\boldsymbol{\sigma}_n$) is the proton (neutron) spin, n and p label the neutron and proton coordinates in the deuteron, and Y and N label the hyperon and nucleon coordinates in the final-state scattering wave function. In our actual calculations we kept in these operators also the momentum-dependent terms proportional to p_p, which were not included in previous work. Such terms introduce a new kind of matrix element and add to the algebraic complexity, but are unimportant numerically. Details are given in Ref. 12.

The factors F_i were deduced from the two-component reduction of the $K^- N \to Y\gamma$ amplitudes with $F_1 \equiv F(K^- p \to \Lambda\gamma)$, $F_2 \equiv F(K^- p \to \Sigma^0\gamma)$, and $F_3 \equiv F(K^- n \to \Sigma^- \gamma)$. They contain the coupling strengths appropriate to the diagrams included as well as various kinematic factors. An explicit expression for the only important one of these, F_1, is given in Eq. (3.51) of Ref. 12 or, in simplified form, Eq. (2.13) of Ref. 11.

The final-state YN wave function is

$$\Psi_j^{(f)} = \frac{1}{(2\pi)^{3/2}} e^{i\mathbf{P}\cdot\mathbf{R}}\psi_j(\mathbf{r}) \ . \tag{6}$$

We approximate the relative Λ-n wave function by its asymptotic form,

$$\psi_j(\mathbf{r}) = \left[\delta_{j1} e^{i\mathbf{p}\cdot\mathbf{r}} + (f_j^s \hat{a}_s + f_j^t \hat{a}_t)\frac{e^{ipr}}{r} \right] |SM\rangle \ . \tag{7}$$

In these expressions R, r, P, and p are, respectively, the center of mass and relative coordinates and momenta, $|SM\rangle$ is the appropriate hyperon-nucleon spin wave function with spin S, and $(\hat{a}_s)$ and $(\hat{a}_t)$ are the singlet and triplet spin projection operators.

The scattering amplitudes f_j are then the s-wave amplitudes for the jth type of final-state interaction, in particular, $f_1 \equiv f_1(\Lambda n \to \Lambda n)$, $f_2 \equiv f_2(\Sigma^0 n \to \Lambda n)$, and $f_3 \equiv f_3(\Sigma^- p \to \Lambda n)$. A detailed calculation of the S matrix for hyperon-nucleon scattering, relating the f_i to the phase shifts, is given in Ref. 12. For our purposes here we approximate the f_i in terms of the s-wave scattering length a and effective range r by the usual formula

$$p \cot\delta = -\frac{1}{a} + \tfrac{1}{2} r p^2 \ , \tag{8}$$

since p, the relative Λ-n momentum, is small near the γ-spectrum endpoint.

With these ingredients it is a straightforward process to evaluate the matrix element of Eq. (1). It can then be squared and summed on spins and on the photon polarization using the standard trace techniques. If we separate M into parts containing the S- and D-state components of the deuteron we find

$$\sum_{\text{spins}} |M|^2 = \sum_{\text{spins}} |M_S + M_D|^2 = \sum_{\text{spins}} |M_S|^2 + 2\,\mathrm{Re}\sum_{\text{spins}} M_S M_D^* + \sum_{\text{spins}} |M_D|^2 \ , \tag{9}$$

where

$$\sum_{\text{spins}} |M_S|^2 = \tfrac{8}{3}\pi\phi_K^2(0)\{3U_0^2|F_1|^2 + U_0 \mathrm{Re}[V_0 F_1^*(3F_+ - F_-)] + \tfrac{1}{4}|V_0|^2(3|F_+|^2 - 2\,\mathrm{Re}(F_+ F_-^*) + 3|F_-|^2)\} \ , \tag{10}$$

$$2\,\mathrm{Re}\sum_{\text{spins}} M_S M_D^* = -\tfrac{8}{3}\sqrt{2}\pi\phi_K^2(0)\mathrm{Re}(\{U_0 V_2 + \tfrac{1}{2}U_2 V_0[3(\hat{p}_n\cdot\hat{k})^2 - 1]\}F_1^* F_- + V_0 V_2^*(F_+ F_-^*)) \ , \tag{11}$$

$$\begin{aligned}\sum_{\text{spins}} |M_D|^2 = \tfrac{8}{3}\pi\phi_K^2(0)\{&3U_2^2|F_1|^2 + \tfrac{1}{2}U_2[3(\hat{p}_n\cdot\hat{k})^2 - 1]\mathrm{Re} V_2 F_1^*(3F_+ - 2F_-) \\ &+ \tfrac{1}{4}|V_2|^2[3|F_+|^2 - 4\,\mathrm{Re}(F_+ F_-^*) + 3|F_-|^2]\} \ .\end{aligned} \tag{12}$$

The $K^- N \to Y\gamma$ strengths and the $YN \to \Lambda n$ scattering amplitudes are contained in F_- and F_+, which are given by[16]

$$F_{\pm} = F_1(f_1^s \pm f_1^t)^* + F_2(f_2^s \pm f_2^t)^* + F_3(f_3^s \pm f_3^t)^* \ . \tag{13}$$

The radial integrals U_0, V_0, U_2, and V_2 containing the usual S- and D-state deuteron wave functions $u(r)$ and $w(r)$ are defined by

$$U_0 = \int_0^{\infty} dr\, r u(r) j_0(p_n r) \ , \tag{14}$$

$$V_0 = \int_0^{\infty} dr\, u(r) j_0(qr) e^{-ipr} \ , \tag{15}$$

$$U_2 = \int_0^{\infty} dr\, r w(r) j_2(p_n r) \ , \tag{16}$$

and

$$V_2 = \int_0^{\infty} dr\, w(r) j_2(qr) e^{-ipr} \ , \tag{17}$$

where p_n is the final neutron momentum and q is related to the photon momentum k by $q = m_n k / (m_n + m_\Lambda)$.

In order to calculate the differential-rate relation, we start with the usual phase space relations and integrate on $d^3 p_n$. The γ spectrum is then found by integrating the result over the allowed range of E_Λ values to obtain

$$\frac{d\Gamma}{dk} = \frac{m_\Lambda m_n}{2(2\pi)^3 (m_K + m_D)} \int_{E_\Lambda(\min)}^{E_\Lambda(\max)} dE_\Lambda \sum_{\text{spins}} |M|^2 \ . \tag{18}$$

III. RESULTS AND DISCUSSION

The aim of this investigation was to see if the spectrum shape near the gamma endpoint would give information about the Λ-n scattering length. To this end it was necessary to look at a large number of effects and ingredients other than the scattering length to see how much effect they had on the spectrum shape. As was the case for the analogous reaction $\pi^- d \to nn\gamma$, a change in almost any of the ingredients of the calculation changes the total rate. However, while this makes a rate calculation difficult, the shape of the spectrum near the end point appears to be relatively insensitive to all ingredients of the calculation except the scattering length. Thus most of these effects can be, and are, neglected in the final results for the spectrum shape given below. Before looking at the results, however, we want to detail the various effects which were considered, and a few things which need further examination.

In the initial state the details of the deuteron wave function are unimportant for the spectrum shape. We used an S-state wave function obtained from the Bonn potential. Including the Bonn D state or using a Hulthen S state produced results which would be indistinguishable on the graphs of our results. The kaon wave function was approximated as a constant, though this may require further consideration as the low-energy $K^- N$ interaction, and thus the short-range behavior of the wave function, is not well understood. In the analogous reaction $\pi^- d \to nn\gamma$, however, this approximation was estimated[8] to change the extracted scattering length at only the few percent level. Things may be more complicated in the $Kd \to \Lambda n\gamma$ reaction, however. Because of the strong attractive potential indicated by the existence of the $\Lambda(1405)$, it has been suggested that the kaon wave function may in fact have a node within the nuclear volume.[17] To estimate the sensitivity to such possible variations in the wave function, we constructed a simple phenomenological wave function which has the expected general properties and used it instead of a constant in the calculation. In particular, the wave function was chosen to have an imaginary part shaped like the deuteron wave function $u(r)$, so that it peaked inside the nuclear volume, and a real part of comparable size with a node also inside the nucleus. Such a wave function changed the normalized photon spectrum in the interesting range 285–293 MeV by at most 20%, with the maximum effect only at the endpoints of the range. Moderate variations of the parameters did not change this result. In particular the size of the effect was not sensitive to whether the wave functions went to zero or to a constant at $r=0$ or to the position of the node in the range 0.5–6 fm. Since the kaon wave function appears under the integral as a product with the deuteron wave function, this lack of sensitivity is consistent with our finding that variations in the deuteron wave function did not affect the shape of the spectrum very much, and with a similar finding in Ref. 8 that a node in the deuteron wave function was not particularly important in the analogous $\pi d \to nn\gamma$ reaction. Nevertheless it is clear that an arbitrarily large variation in the kaon wave function could make an arbitrarily large change in the results even for the shape. Thus in the next generation calculation of this process, when hopefully enough information will be available on the low-energy KN interaction to actually calculate a realistic Kd wave function, such a realistic wave function should certainly be used.

Details of the radiative capture operator $\hat{T}$ also appear to be unimportant. In particular, our extension of the basic operator to include momentum-dependent pieces again produced results almost indistinguishable from those given below. Thus the Fermi motion within the deuteron has little effect on the spectrum shape. Likewise the $O(k/m)$ terms originating from the basic interactions $K^- N \to Y\gamma$ and thus contained in the factors F_i did not affect the shape of the spectrum appreciably. This means that contributions to the basic process from higher resonances and in particular from the $\Lambda(1405)$ and uncertainties in the couplings are unimportant. For the results below we used the Born contributions of Ref. 11.

In the final state the first observation is that only the $K^- p \to \Lambda\gamma$ capture process is important as the other channels, $K^- p \to \Sigma^0\gamma$ and $K^- n \to \Sigma^-\gamma$, contribute significantly only much below the endpoint of the photon spectrum, since the threshold photon energies are 225 MeV and 222 MeV, respectively. (This insensitivity of the spectrum shape can also be seen in Fig. 3 of Ref. 10.) Thus we need only include f_1, the rescattering amplitude for $\Lambda n \to \Lambda n$.

As noted above, f_1 is evaluated in an s-wave scattering length and effective range approximation. We have estimated contributions from the p wave, but these appear to be rather small for the kinematic conditions corresponding to the spectrum endpoint. For example Nagels

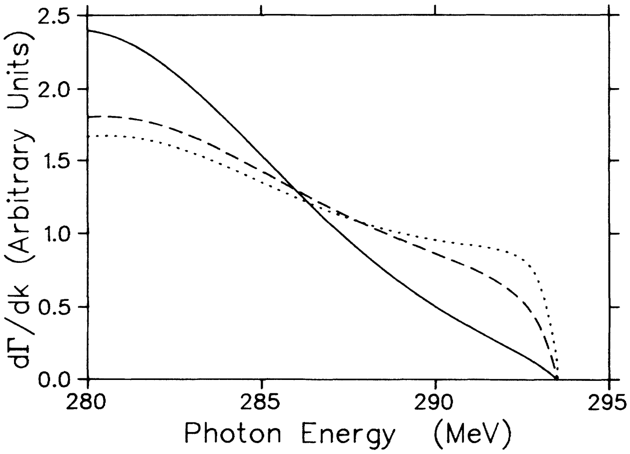

FIG. 1. Photon spectrum normalized to constant area, for several sets of triplet and singlet Λ-n scattering lengths and effective ranges in fm. The curves have $a_s=0$, $a_t=0$, $r_s=0$, $r_t=0$ (solid line); $a_s=-2.40$, $a_t=-1.84$, $r_s=3.15$, $r_t=3.37$ (dashed line); $a_s=-5.0$, $a_t=-3.0$, $r_s=3.5$, $r_t=3.5$ (dotted line).

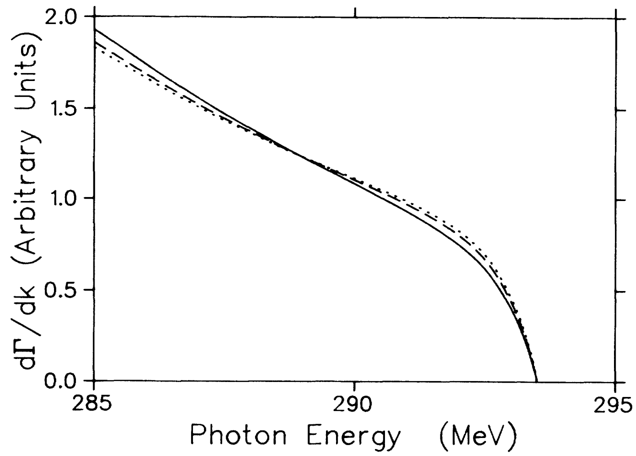

FIG. 2. Photon spectrum normalized as in Fig. 1. The curves have $a_s=-2.67$, $a_t=-1.02$, $r_s=2.04$, $r_t=2.55$ (solid line); $a_s=-2.03$, $a_t=-1.84$, $r_s=3.66$, $r_t=3.32$ (dashed line); $a_s=-2.40$, $a_t=-1.84$, $r_s=3.15$, $r_t=3.37$ (dotted line).

et al.[18–20] find that the *s*-wave scattering length is about -2 fm, whereas the corresponding *p*-wave quantity is less than 0.2 fm^3. In addition, the *p*-wave amplitude goes to zero at the high-energy endpoint of the photon spectrum. Finally, reasonable variations in the effective range are not important for the shape. Changes of ± 1 fm give results nearly indistinguishable from those given below.

Finally, one other approximation should be mentioned, namely the use of the asymptotic form for the Λ-n scattering state. This neglects short-range variations in the wave function. Such variations should be suppressed by the sharp decline of the deuteron *S*-state wave function below 1 fm. However, this may warrant further consideration, as it was found[8] in the $\pi^- d \rightarrow nn\gamma$ reaction that the uncertainty in the short-range *n*-*n* wave function contributed a sizable fraction of the theoretical uncertainty in the extraction of a *n*-*n* scattering length.

We can now show some of the results of these calculations. Figure 1 displays the photon spectrum near its endpoint normalized to equal area in order to isolate differences in its shape. The solid curve corresponds to a situation with no Λ-n final-state interaction, while the dashed curve corresponds to the Λ-n scattering parameters obtained from the potential model of Nagels *et al.*[18] and the dotted curve to a somewhat larger scattering length. Clearly the shape of the spectrum near the endpoint is sensitive to the Λ-n scattering length. In view of the insensitivity to other ingredients in the calculation this should be, given sufficiently accurate data, a relatively clean way to extract the scattering lengths, just as was the case for $\pi^- d \rightarrow nn\gamma$.

Preliminary results from the experimental group[5] working at Brookhaven, while hampered by a large background and low statistics, appear to suggest evidence for a nonzero scattering length, when analyzed in terms of these calculations. The separation of various models differing by small amounts will be much more difficult, however, as is illustrated in Fig. 2. Here photon spectra derived from three sets of Λ-n scattering parameters are compared. The solid, dashed, and dotted lines correspond to the parameter sets of Refs. 19, 20, and 18, respectively. Clearly a separation of scattering lengths at the level of a few tenths of a fm will require much better experiments than possible with existing kaon beams.

Finally, as the spectrum shape is dependent on both the singlet and triplet Λ-n scattering lengths, it would be desirable to measure a second quantity, such as the Λ or photon polarization, in order to isolate the singlet and triplet contributions. Such an experiment would also require the improved beams at one of the proposed kaon factories.

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