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Radiative kaon capture on nuclei

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Hypernuclear formation through the radiative capture of in-flight K^- is studied in a distorted wave impluse approximation approach. The elementary operator is obtained from first-order Feynman diagrams and is constrained by the reactions $K^-p \rightarrow \Lambda\gamma$ and, via crossing, by $\gamma p \rightarrow K^+\Lambda$. The K^- distortion has been included via a simple optical potential which is in agreement with K^- elastic scattering on nuclei. Using the reaction $^{16}O(K^-,\gamma)^{16}_{\Lambda}N$ we obtain cross sections up to 10 μb for photons emitted at forward angles.

In recent years, several studies on the radiative kaon capture by protons have appeared[1-4] motivated in part by a new and more precise determination of the $K^-p \rightarrow \Lambda\gamma$ and $K^-p \rightarrow \Sigma^0\gamma$ branching ratios measured at Brookhaven.[5] One primary focus was on the role of the poorly understood $\Lambda(1405)$ state since different theoretical models[2,3] yield very different contributions from this subthreshold resonance. Furthermore, the radiative capture reaction has been related to kaon photoproduction, $\gamma p \rightarrow K^+\Lambda$, employing the crossing symmetry.[4,6] Since crossing related reactions are described by the same transition amplitude evaluated in different kinematic regions of the S matrix, they should be analyzed with the same set of strong coupling constants.

After the K^- capture reaction on the proton has been investigated in several papers[1-4] we focus in this study on the radiative K^- capture on nuclei leading to the formation of hypernuclear states. Except for a short study with stopped K^- almost 20 years ago,[7] no cross sections have been presented for this process. With the upcoming of "kaon factories" which will provide intense kaon beams these reactions may become feasible. Radiative kaon capture is one of the simplest reactions involving strange particles and has the advantage that one of the vertices involves the electromagnetic interaction, and can therefore be treated perturbatively. Once the role of hyperon resonances such as the $\Lambda(1405)$ has been clarified in the elementary process with stopped and in-flight K^-, one might look for possible modifications in the nuclear medium via the (K^-,γ) reaction on nuclei. Furthermore, in contrast to the $(K^-,\pi^\pm)$ process, the exciting photon is only weakly perturbed; thus K^- capture reactions can complement information on hypernuclei that has been obtained with purely hadronic probes.

The differential cross section for the radiative capture of in-flight K^- can be obtained by applying crossing symmetry and time reversal invariance to the cross section of (γ,K^+) on nuclei given in Ref 8. As in previous kaon photoproduction studies we employ particle-hole wave functions to describe the nuclear and hypernuclear structure. However, as shown in Ref. 9, diagonalizing the ΛN interaction can give important contributions, especially for lambda orbits which are barely bound; thus configuration mixing and the coupling to the continuum should be included in a more sophisticated calculation.

We proceed to evaluate the single particle matrix elements[8] which we calculate in momentum space. This ensures the proper treatment of Fermi motion and, furthermore, allows the straightforward inclusion of nonlocalities resulting from the propagation of the various baryons in the elementary production operator. Using the impulse approximation we arrive at

$$\langle f,\gamma|t|i,K^-\rangle = \int d^3p\, d^3q'\, \psi_f^*(\mathbf{p}')\, t_{K^-p\rightarrow\Lambda\gamma}(\mathbf{p}',\mathbf{p},\mathbf{k},\mathbf{q}') \times \Phi_{K^-}^{(+)}(\mathbf{q},\mathbf{q}')\psi_i(\mathbf{p}) \ , \tag{1}$$

where $t_{K^-p\rightarrow\Lambda\gamma}$ is the elementary amplitude, and $\mathbf{p}$, $\mathbf{q}'$, $\mathbf{k}$, and $\mathbf{p}'=\mathbf{p}+\mathbf{q}'-\mathbf{k}$ are the momenta of the proton, kaon, photon, and lambda. The proton and lambda wave functions ψ_i and ψ_f are obtained by solving the Schrödinger equation with standard central and spin-orbit potentials of Wood-Saxon shape, whose geometries have been adjusted to fit binding energies and form factors. The wave function with the appropriate boundary condition for the incoming K^- with asymptotic momentum $\mathbf{q}$ distorted by its interaction with the nucleus through an optical potential is denoted by $\Phi_K^{(+)}(\mathbf{q},\mathbf{q}')$.

In contrast to the situation for the K^+, the K^-N system is strongly interacting,[10] since it can fuse to form Y^* resonances which can communicate with the $\Lambda\pi$ and $\Sigma\pi$ channels even at the K^-N threshold. The K^- is therefore a strongly absorbed particle comparable to the pion in the region dominated by N^* resonances. In order to include the K^--nucleus interaction we define a local optical potential of the form[11]

$$-2E_K V(r) = p_{\mathrm{lab}}^2 b_0 \rho(r) \ , \tag{2}$$

where E_K is the K^- total energy, p_{lab} is the K^- lab momentum, and $\rho(r)$ the nuclear density. At $p_{\mathrm{lab}}=800$ MeV/c the K^-N amplitudes are rapidly varying and D waves are non-negligible. The parameter b_0 therefore includes S, P, and D wave contributions to the total K^-N isospin-averaged forward amplitude;[12] at 800 MeV/c we adopt the Fermi-averaged value of Ref. 11, $b_0=0.51+0.87i$ fm^3.

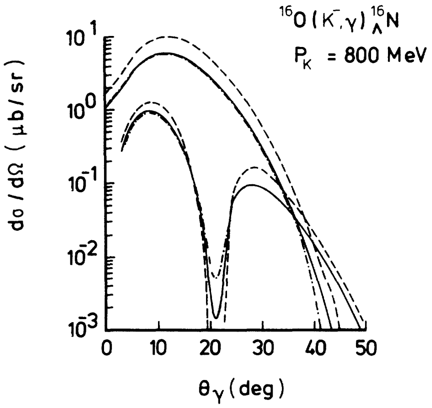

FIG. 1. Angular distributions comparing different models of the elementary amplitude for the $(p_{1/2}^{-1},s_{1/2})1^-$ ground state (upper curves) and the $(p_{3/2}^{-1},p_{3/2})0^+$ state (lower curves). The solid (dashed, dash-dotted) curves show calculations with model $C2$ (model WF, model AW IV) of Table I.

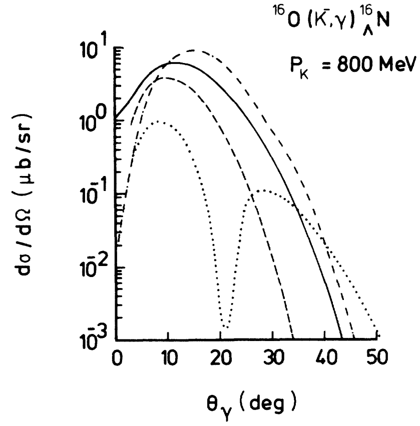

FIG. 2. Cross sections for different transitions in the process ^{16}O$(K^-,\gamma)^{16}_{\Lambda}$N. The solid (dashed, dotted, dash-dotted) curve shows the transition to the $(p_{1/2}^{-1},s_{1/2})1^-$ $[(p_{1/2}^{-1},s_{1/2})0^-$, $(p_{3/2}^{-1},p_{3/2})0^+$, $(p_{3/2}^{-1},p_{3/2})3^+]$ state.

In order to evaluate the single particle matrix element of Eq. (1) we need an elementary transition operator for the process $K^-p\rightarrow\Lambda\gamma$. Except branching ratios obtained with stopped K^-, no experimental data are available for this reaction. However, a recent analysis related K^- radiative capture to K^+ photoproduction by incorporating crossing symmetry.[4,6] A number of models have been developed for the process $\gamma p\rightarrow K^+\Lambda$ within the past years.[4,6,13–15] They are mostly based on Feynman diagrams which include the Born terms plus a few low-lying baryon and meson resonances whose coupling constants have been adjusted to reproduce experimental data. While a similar pole-model calculation has been performed independently for the $K^-p\rightarrow\Lambda\gamma$ branching ratio,[1] Ref. 4 has used all available data from both reactions to obtain one consistent set of coupling constants.

In Fig. 1 we compare three different elementary amplitudes in the reaction ^{16}O$(K^-,\gamma)^{16}_{\Lambda}N$ at $p_K=800$ MeV/c for two different states. The models include the Born terms along with the K^* and Σ exchange, as well as the

TABLE I. Different parameter sets used in the calculation. For the definition of the coupling constants, see Ref. 13 or Ref. 4.

Model	$C2$ (Ref. 4)	AW IV (Ref. 14)	WF (Ref. 1)
g_Λ	10.581	11.166	−13.187
G_Σ	11.590	11.627	11.812
G_V	0.323	0.339	−1.147
G_T	−1.791	−2.362	−4.218
G_V^{K1}	1.986	1.659	0
G_T^{K1}	0.364	0.792	0
G_{Y1}	1.862	0	−1.7
G_{Y2}	−1.503	2.474	0.059
G_{Y3}	0.703	0	0.255
G_{N1}	−2.104	−3.935	0
G_{N4}	0.273	0.358	0.358
G_{N6}	0.037	0	0

N^* resonances $P_{11}(1440)$, $S_{11}(1650)$, $P_{11}(1710)$ and the Y^* resonances $S_{01}(1405)$, $S_{01}(1670)$, $S_{01}(1800)$ which we name, as in Ref. 4, $N1$, $N4$, $N6$, $Y1$, $Y2$, and $Y3$, respectively. Furthermore, the t-channel resonance $K1(1280)$ is included since this state is needed[14] to obtain, when fitting the (γ,K^+) data, a value for the leading coupling constant $g_{K\Lambda N}$ which is closer to the one extracted from K^-p and K^+p scattering and the SU(3) prediction. Alternatively, one might incorporate $K^+\Lambda$ final state absorptive effects[15] which cause a strong suppression of the Born terms and allow $g_{K\Lambda N}$ to have its standard value. However, it is difficult to include crossing in such an approach since the absorptive effects in the $K^+\Lambda$ system are clearly different from those in the K^-p system. We therefore choose the models of Refs. 1 and 14 for comparison in Fig. 1. The coupling constants are given in Table I. Surprisingly, we find that the model $C2$, which is constrained by the K^-p branching ratio as well as (γ,K^+) data, and AW IV give almost identical results even though model AW IV overestimates the experimental K^-p branching ratio by a factor of 4. On the other hand, model WF, unconstrained by the (γ,K^+) data, yields angular distributions more than 50% higher than the other two predicting almost 10 μb/sr at the maximum. We will employ model $C2$ for the calculations shown below.

Figure 2 compares the cross sections of several different ground and excited state transitions in the process ^{16}O$(K^-,\gamma)^{16}_{\Lambda}$N. As in the (γ,K^+) reaction the momentum transfer to the residual hypernucleus rises rapidly for increasing photon angles leading to angular distributions which are forward-peaked and fall off rapidly for large photon angles. We also find that high spin states such as the $(p_{3/2}^{-1},p_{3/2})3^+$ are preferentially excited while states like the $(p_{3/2}^{-1},p_{3/2})0^+$ have smaller cross sections but exhibit some structure.

Finally, we present in Fig. 3 a comparison between a DWIA and a PWIA calculation. Except at very forward angles, K^- optical distortion leads to a decrease of the cross section up to a factor of 2. As discussed above, this

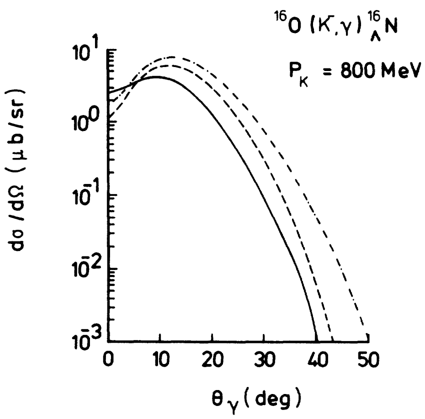

FIG. 3. Cross sections for the $(p_{1/2}^{-1},s_{1/2})1^-$ ground state comparing the nonlocal DWIA calculations (solid curve) with the nonlocal and local PWIA computation (dashed and dash-dotted curve, respectively).

is in contrast to DWIA computations for (γ,K^+) processes where the K^+ final state interaction affects cross sections by at most 30% for p-shell nuclei.[8,9] Furthermore, we show a PWIA calculation performed in the local "frozen nucleon" approximation to emphasize the importance of properly including Fermi motion. The difference between the local and nonlocal calculation increases for larger photon angles but is also significant for a number of low spin states with smaller cross sections and diffraction minima, as we have verified.

In conclusion, we have presented cross sections and angular distributions for radiative K^- capture on nuclei. The calculations were performed in a DWIA framework carried out in momentum space. We find fairly large cross sections at forward photon angles especially for high spin states. Once the (γ,K^+) data are included as a constraint on the elementary amplitude via crossing there appears to be little model dependence in the predicted angular distributions. K^--distortion effects as well as nonlocalities are significant and should be included properly. However, an improved calculation should include more sophisticated hypernuclear many-body wave functions in order to obtain realistic predictions which could then be compared directly to the experiment.

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