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Kaon charge exchange on ^{3}H

Manuel J. Páez* and Rubin H. Landau
Department of Physics, Oregon State University, Corvallis, Oregon 97331
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The single charge exchange reaction ^{3}H(K^+,K^0)^{3}He is examined with a theoretical momentum space optical potential including realistic form factors for the distribution of matter and spin in the nucleus. The K^+-nucleon amplitudes are calculated from two body phase shifts and extrapolated off shell with separable potentials. The elementary charge exchange amplitudes have large P and D wave parts and a large spin flip component. Differential and total cross sections for charge exchange from ^{3}H are presented for kaon energies from 0.4 to 1 GeV, and the sensitivity to the nuclear form factors is found to be high for appropriate kinematical conditions.

[NUCLEAR REACTIONS ^{3}H(K^+,K^0)^{3}He; $E = 39-804$ MeV; $\sigma(\theta)$ and σ_{tot}; theoretical calculation, momentum space optical potential; spin effects, subenergy shifts.]

I. INTRODUCTION

It is not an easy matter to learn about nuclei by scattering a strongly interacting projectile from them.[1] For this reason nuclear physicists are usually curious about the properties and sensitivities of any new projectile in order to confirm the findings of previous (i.e., conventional) probes or probe normally inaccessible aspects of nuclear structure. Within the last few years theoretical investigations have examined the properties of the kaon interaction with nucleons and nuclei in order to determine their usefulness as a probe[2–10] complementary to the nucleon and pion. These works are illuminating and stimulating to the experimental studies just now underway.[9,10]

In this paper we extend our previous examination of K^+ elastic scattering from ^{3}He, ^{3}H, ^{4}He, and ^{12}C[11] to include also the single charge exchange reaction ^{3}H(K^+,K^0)^{3}He. These examinations are both paths in a unified investigation of $\pi^\pm$, p, n, and $K^\pm$ interactions with light nuclei which aims to increase the reliability of deduced nuclear structure information. Since similar calculations of the ^{3}H(π^+,π^0)^{3}He and ^{13}C(π^+,π^0)^{13}N reactions show high sensitivity to nuclear structure and some unique aspects of the theoretical formulation (core excitation, Coulomb splitting of energy dependent potentials, etc.), the (K^+,K^0) reaction is interesting for its own sake, and as a complement to the pion studies.

II. THEORY

Our approach is based on a momentum space optical potential description of spin $0 \otimes \frac{1}{2}$ scattering, which we described in more detail elsewhere.[11] In the impulse approximation the central and spin dependent parts of the first order potential are expressed in terms of KN t matrices and nuclear matter and spin form factors of momentum transfer $\vec{q} = \vec{k}' - \vec{k}$:

$$U_C(\vec{k}'\,|\,\vec{k}) = \frac{A-1}{A}[\langle f\,|\,t^{Kp}(\omega)\,|\,i\rangle Z\rho^{p}_{\rm mat}(q) + \langle f\,|\,t^{Kn}(\omega)\,|\,i\rangle N\rho^{n}_{\rm mat}(q)]\,, \quad (1)$$

$$U_S(\vec{k}'\,|\,\vec{k}) = \frac{A-1}{A}[\langle f\,|\,t^{Kp}_{\rm flip}\,|\,i\rangle Z\rho^{p}_{sp}(q) + \langle f\,|\,t^{Kn}_{\rm flip}(\omega)\,|\,i\rangle N\rho^{n}_{sp}(q)] \times i\vec{\sigma}\cdot(\hat{k}\times\hat{k}')\,. \quad (2)$$

The nucleon momenta variables in $\langle t \rangle$ are determined to provide an optimal factorization approximation, the KN c.m. four-momenta are determined with a separate Lorentz transformation for the initial and final states, and the KN subenergy $\tilde{\omega}$ (in the KN c.m.) is given by the three body prescription.[11,12] The Martin phase shifts[13] are used to calculate the on-shell KN amplitudes, and a separable potential model is used to determine their off-energy shell behavior in each eigenchannel. Since the main emphasis of the present paper concerns nuclear structure effects, we again refer the reader to Refs. 11 and 2–10 for discussions of the relatively low sensitivity of the calculation to these choices and approximations.

The matter and spin form factors of ^{3}He, including S, S', and D states, are deduced from Schiff and Gibson's[14] study of the electromagnetic form factors, with the form factors for the mirror nucleus ^{3}H obtained by the interchange $p \rightleftarrows n$. If we assume a single, effective, SD component, and set to zero: (1) the very small DD terms, (2) the neutron charge form factor, and (3) exchange current contributions, we obtain[15]

$$\rho^p_{\mathrm{mat}}(q) \cong F_{\mathrm{ch}}(^3\mathrm{He})/f_{\mathrm{ch}}(p)\ , \tag{3}$$

$$\rho^n_{\mathrm{mat}}(q) \cong F_{\mathrm{ch}}(^3\mathrm{H})/f_{\mathrm{ch}}(p)\ , \tag{4}$$

$$\rho^n_{\mathrm{sp}}(q) \cong \frac{\mu_n}{2(\mu_p+2\mu_n)f_{\mathrm{ch}}(p)}\left\{2F_{\mathrm{mag}}(^3\mathrm{He}) + \frac{\mu_p}{3\mu_n}[4F_{\mathrm{ch}}(^3\mathrm{He}) - F_{\mathrm{ch}}(^3\mathrm{H})]\right\} \tag{5}$$

$$\rho^p_{\mathrm{sp}}(q) \cong \frac{\mu_n}{2(\mu_p+2\mu_n)f_{\mathrm{ch}}(p)}\{F_{\mathrm{mag}}(^3\mathrm{He}) - \tfrac{1}{3}[4F_{\mathrm{ch}}(^3\mathrm{He}) - F_c(^3\mathrm{H})]\} \tag{6}$$

$$\mu_p = 2.793\mu_N,\ \ \mu_n = -1.913\mu_N\ .$$

Although we must keep in mind that Eqs. (3)–(6) may lose their validity at the very high momentum transfers obtained with high energy kaons, they are valid for most q and do permit the direct use of the experimental three nucleon form factors in our calculation. In the future, these assumptions can be improved, or when fundamental calculations of the three nucleon wave function are able to reproduce the large q behavior of the electromagnetic form factors,[16] theoretical $3N$ wave functions can be used.

The experimental charge and magnetic form factors of ^{3}He are taken as the analytic fit of McCarthy *et al.*[17]:

$$F_{\mathrm{ch,mag}}(^3\mathrm{He}) = \exp[-a^2q^2] - b^2q^2\exp[-c^2q^2] + d\exp\left[-\left[\frac{q-q_0}{q_1}\right]^2\right]\ , \tag{7}$$

$$a_{\mathrm{ch,mag}} = (0.675,\ 0.654)\ \mathrm{fm},\ \ b_{\mathrm{ch,mag}} = (0.366,\ 0.456)\ \mathrm{fm},\ \ c_{\mathrm{ch,mag}} = (0.836,\ 0.821)\ \mathrm{fm}\ ,$$

$$d_{\mathrm{ch,mag}} = (-6.78\times10^{-3},0),\ \ (q_0,q_1) = (3.98,\ 0.90)\mathrm{fm}^{-1}\ .$$

For the $F_{\mathrm{ch}}(^3\mathrm{H})$ we use the actual data points of Collard *et al.*[18] for $q^2 \leq 8\ \mathrm{fm}^{-2}$, for $8 < q^2 < 16\ \mathrm{fm}^{-2}$ we use McMillan's three nucleon wave functions,[19] and for $q^2 > 16\ \mathrm{fm}^{-2}$ we assume a continuous Gaussian dropoff. Since McMillan's wave functions fit $F_{\mathrm{ch}}(^3\mathrm{He})$ fairly well in the range $8 < q^2 < 12\ \mathrm{fm}^{-2}$, our input should be fairly reliable there; at larger q^2 they are at best reasonable extrapolations.

To calculate the single charge exchange (CEX) scattering amplitude we use the $\frac{1}{2}\otimes\frac{1}{2}$ isospin structure of the K^+-$3N$ amplitude to relate it to the elastic amplitudes:

$$T(K^{+\,3}\mathrm{H}\rightarrow K^{0\,3}\mathrm{He}) = \tfrac{1}{2}[T(I=1) - T(I=0)] \tag{8}$$

$$= T^{\mathrm{el}}(K^{+\,3}\mathrm{He}) - T^{\mathrm{el}}(K^{0\,3}\mathrm{He})\ , \tag{9}$$

i.e., nuclear analog of the elementary relation:

$$T(K^+n\rightarrow K^0p) = T(K^+p) - T(K^0p)\ . \tag{10}$$

Although Eqs. (8) and (9) are based on a perfect isospin symmetry (which our truncated, single channel calculation does not possess), Thomas and Landau[20] have indicated that they are equivalent to the standard distorted-wave impulse approximation (DWIA) result,

$$T(K^+\,{}^3\mathrm{H}\rightarrow K^0\,{}^3\mathrm{He})=\Omega^{(+)}[U^{\mathrm{el}}(K^+\,{}^3\mathrm{He})-U^{\mathrm{el}}(K^0\,{}^3\mathrm{He})]\Omega^{(0)}\,. \quad (11)$$

If we substitute Eqs. (1) and (2) for the optical potential into Eq. (11), we obtain the expected result that the nuclear CEX amplitude is related to the elementary CEX amplitude, the difference in n and p form factors, and the appropriate distortion factors:

$$T(K^+\,{}^3\mathrm{H}\rightarrow K^0\,{}^3\mathrm{He})=\Omega^{(+)}[t^{\mathrm{CEX}}(KN)(Z\rho_p-N\rho_n)]\Omega^{(0)}\,. \quad (12)$$

The largest approximation in our application is that $\Omega^{(+)}$ contains the distortion produced by ^{3}He and not ^{3}H (the two are very similar[11]) but none of the distortion produced by the Coulomb force. As expected, Gerace *et al.*[21] have verified Eq. (9) to be an excellent approximation to a coupled channels calculation [the only significant differences occur at low energies where the optical model of Ref. 21 breaks down].

Since an elementary KN charge exchange lies at the core of our calculation, we show these elementary S-F wave KN CEX amplitudes in Fig. 1 (all calculated with the Martin phases). Since these elementary CEX amplitudes are about half the magnitude of the already weak elastic ones,[2,5,8,11] the ^{3}H$(K^+,K^0)^3$He reaction is weaker than the ^{3}H$(K^+,K^+)^3$H one. However, the structure of the CEX amplitudes is quite different—and in many ways more interesting—than the elastic amplitudes, which are simply dominated by the S wave, nonflip amplitudes. For example, above 500 MeV/c (220 MeV) the S waves no longer dominate CEX scattering [Figs. 1(a) and 1(b)], with the D and F waves even becoming important above $\sim$800 MeV/c (446 MeV). Most interesting to us is Fig. 1(c) which shows the very large strength of spin flip scattering (stronger than nonflip) even for energies as low as 142 MeV (400 MeV/c). However, a caveate is appropriate here; since the elastic KN amplitudes vary significantly from analysis to analysis, we expect even larger uncertainties in the CEX reaction, which employs differences of amplitudes.

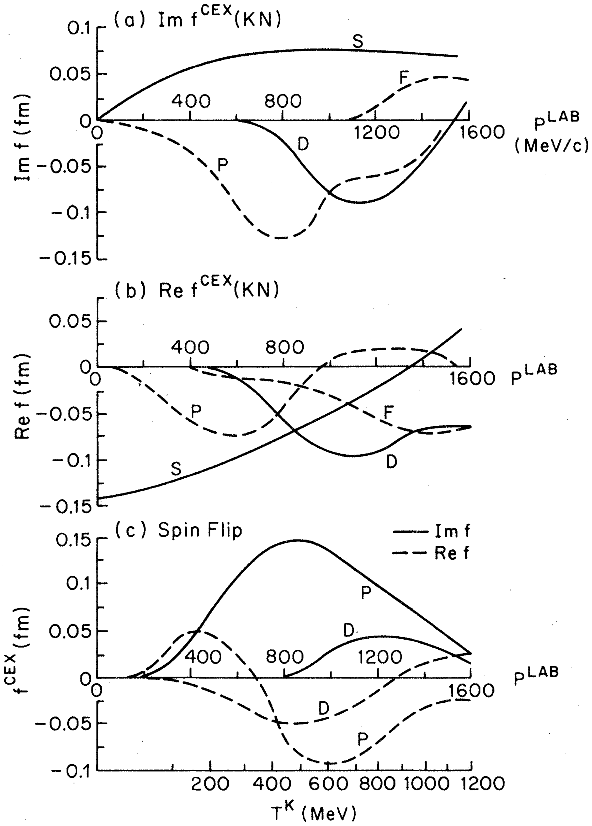

FIG. 1. The $K^+n\rightarrow K^0p$ CEX scattering amplitude for the S-F partial waves as a function of laboratory momentum and energy. (a) imaginary parts of nonflip, (b) real parts of nonflip, and (c) the spin flip amplitude.

III. RESULTS

In Ref. 11 we showed that elastic K^+ scattering from ^{3}He and ^{3}H contains little multiple scattering and is dominated by the elementary K^+p and K^+n S wave amplitudes, as is true for other nuclei.[2–10] Consequently, spin effects are rather small, and the elastic scattering appears to be most sensitive to the nuclear matter distributions, i.e., to the charge form factors of ^{3}He and ^{3}H. In Fig. 2 we see (solid versus dot-dashed curves) that the charge exchange scattering is also mainly single scattering (SS),

$$T\approx T^{\mathrm{SS}}\equiv U_c(\vec{k}'\,|\,\vec{k})+U_s(\vec{k}'\,|\,\vec{k})\,, \quad (13)$$

except at the largest momentum transfers where the miniscule size of the Gaussian-type, nuclear form factor makes two scatterings of $\vec{q}/2$ [with weight $\rho(q/2)^2$] more likely than one weighted by $\rho(q)$. On the other hand, spin flip scattering is now very large for $\theta_{\mathrm{c.m.}}\lesssim 100°$ (dashed versus solid curve), a direct consequence of the large $K^+n\rightarrow K^0p$, P wave, spin-flip amplitude shown in Fig. 1, and of the cancellation of some of the "matter" density terms inherent in Eq. (12).[22]

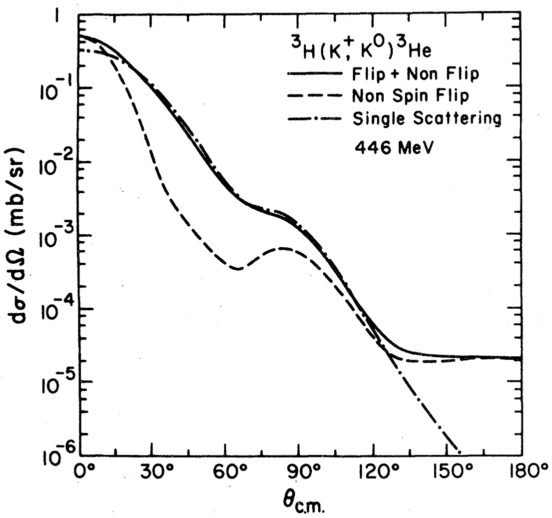

FIG. 2. The differential cross section for the ^{3}H(K^+,K^0)^{3}He reaction at 446 MeV: solid curve—spin flip and nonflip scattering, dashed curve—nonflip only, and dot-dashed curve flip and nonflip terms in the single scattering approximation.

Since the (K^+,K^0) reaction contains a large contribution from spin flip scattering, it should be sensitive to the spin form factors of the nucleus, Eqs. (5) and (6), and consequently to our input ^{3}He magnetic (and charge) form factors. To gauge this sensitivity, we repeated our calculations employing form factors evaluated with the size parameters at their respective upper and lower limits (e.g., $a_m = 0.654 \pm 0.024 = 0.678, 0.630$).

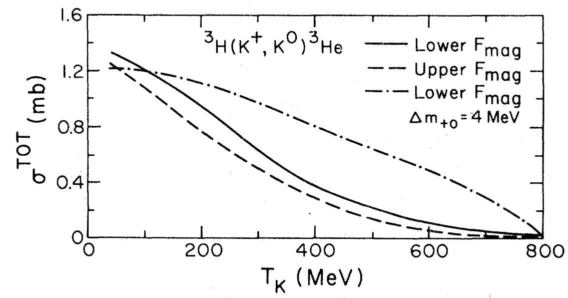

FIG. 4. The total CEX cross section as a function of beam energy for two different sizes of the input $F_{\rm mag}(^3{\rm He})$, and a variation of 4 MeV in the K^+ and K^0 subenergies (heavy dashed curve).

In Fig. 3 we see that the ^{3}H(K^+,K^0)^{3}He differential cross section shows a high sensitivity (factor of 3) in the forward hemisphere for $140 < T_K < 800$ MeV. (The large difference in magnitude of the 39 MeV and higher energy cross sections shows that more than *KN S* waves are important.) Likewise, in Fig. 4 (solid versus dashed curve) we see that the integrated CEX cross section also shows a quite significant ($\sim 25-50\,\%$) variation when the input $F_{\rm mag}(^3{\rm He})$ is varied. In contrast, Fig. 5 indicates that the sensitivity of (uncertainty in) our calculation arising from the variation of the *charge* form factor occurs in the backward hemisphere (larger momentum transfer), with behavior quite similar to that found for elastic scattering.[11]

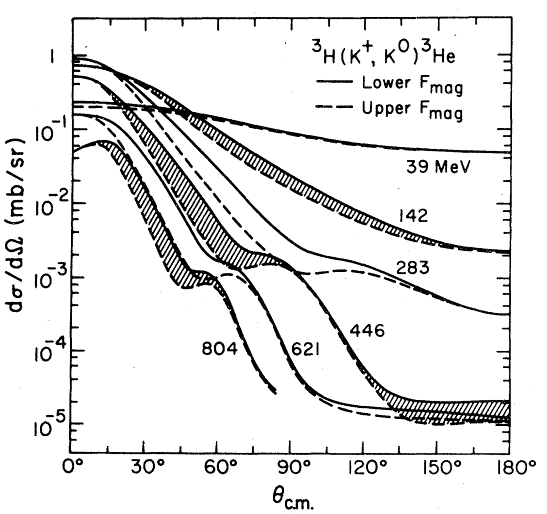

FIG. 3. K^+ ^{3}H charge exchange scattering for $E = 39-804$ MeV calculated with spin distributions obtained by varying the parameters in the input $F_{\rm mag}(^3{\rm He})$.

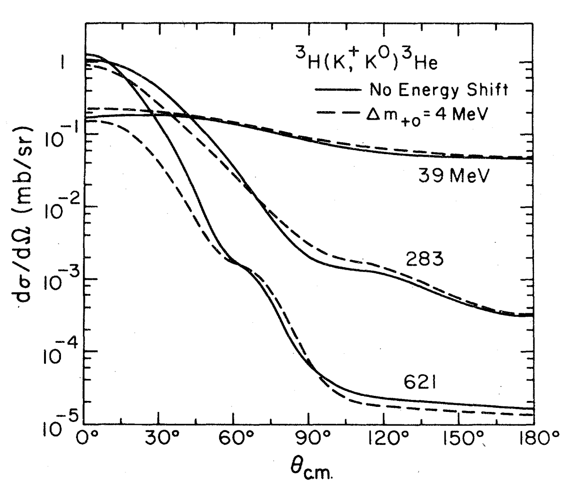

FIG. 5. K^+ ^{3}H CEX scattering at 446 MeV calculated with upper and lower values for the input *charge* form factor $F_{ch}(^3{\rm He})$.

In earlier studies of the (π^+,π^0) reaction it was found[23,20] that the predicted total cross sections are sensitive to differences in the energy parameter of the optical potential for different isospin channels. These energy shifts can arise from a number of effects, e.g., core excitations, binding corrections to the impulse approximation, or Coulomb force breaking of isospin symmetry; all effects which increase CEX scattering by permitting it to occur on more than just the valent nucleon [i.e., the core contributes to the $\rho_p - \rho_n$ in Eq. (12)]. Although these shifts are rather phenomenological at present, they may signal some interesting new physics which appears to occur for a variety of probes,[24] and may well warrant microscopic study in the future.

For the above reasons we investigate the sensitivity of the ^{3}H$(K^+,K^0)^3$He reaction to channel energy differences by evaluating the K^0N amplitudes at a subenergy $\tilde{\omega}$, some 4 MeV higher than for the K^+N amplitudes [since $m(K^0) - m(K^+) = 4.01$ MeV, this should be an appropriate size for a sensitivity study]. In Fig. 6 we see that this shift produces large effects in the differential cross section, and correspondingly large effects in the total cross section (dot-dashed curve in Fig. 4). The sensitivity is particularly large at 621 MeV (1000 MeV/c), which can be understood by examining the elementary K^+-nucleon elastic scattering amplitudes (Fig. 1 of Ref. 11) and the elementary $K^+n \to K^0p$ amplitude, Fig. 1. Since at 1000 MeV/c, $\mathrm{Im}T^p(L=0) \cong \mathrm{Im}T^n(L=1)$, $\mathrm{Im}T^n(L=0) \cong \mathrm{Im}T^p(L=1)$, $\mathrm{Re}T^n(L=1) \cong \mathrm{Re}T^p(L=1)$, and $\mathrm{Re}T^n(L=0) \cong \mathrm{Re}T^p(L=0)$, a slight shift in energy can easily change the degree of cancellation (at $\theta \cong 0°$) of these amplitude pairs .

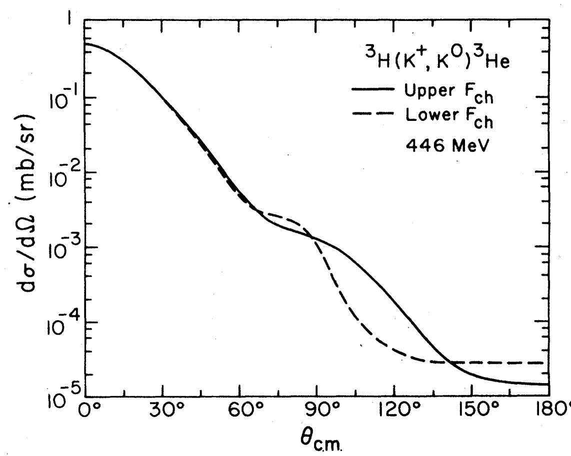

FIG. 6. The effect of the $K^+ - K^0$ subenergy shift on the differential charge exchange cross sections.

IV. SUMMARY AND CONCLUSIONS

We have seen that over the energy range from 0 to ~ 1 GeV the K^+-nucleon CEX scattering amplitude is weak ($\lesssim 0.1$ fm), yet contains large contributions from P and D waves and from spin flip. This leads to cross sections for ^{3}H$(K^+,K^0)^3$He which qualitatively are similar to those of a single scattering approximation and thus should not be sensitive to higher order corrections such as coupled channels effects. In addition, for $T_K \gtrsim 150$ MeV and $\theta_{\mathrm{c.m.}} \lesssim 90°$, the ^{3}H charge exchange cross section contains a large and well separated contribution from spin flip scattering which leads to a high sensitivity to the nuclear distribution of spin. At larger momentum transfers (i.e., the backward hemisphere), the reaction shows sensitivity to the proton matter distribution. For heavier nuclei such as ^{13}C, on a percentage basis we expect much smaller spin effects.

Although the experimental study of the ^{3}H$(K^+,K^0)^3$He reaction is difficult, it would be a most valuable complement to any elastic scattering study and should be feasible at a kaon "factory." At present the greatest theoretical uncertainties lie in the elementary KN input amplitudes, and in the three-nucleon charge and magnetic form factors at large momentum transfers; uncertainties which could be removed by the elastic scattering studies.

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*On leave from Departamento de Física, Universidad de Antioquia, Medellín, Colombia.

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