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K^+ as a probe of partial deconfinement in nuclei

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It is shown that conclusions can be drawn in regard to fundamental structure of nuclear material from the scattering of K^+ mesons from nuclei. A calculation of the ratio K^+-carbon to K^+-deuteron total cross sections is presented which includes traditional medium corrections and their uncertainties. That this calculation falls well below the available data suggests more exotic mechanisms. In particular, models for the distribution of quarks involving an increased confinement range can be tested. Treatment of the K^+ either via an optical model or in a multiple scattering expansion approach yields equivalent results.

I. INTRODUCTION

In the conventional view of nuclear physics, a nucleon's size, form factor, mass, magnetic moment, and other internal properties are unchanged when it is embedded in a nucleus. The substantial success of low energy nuclear physics calculations confirms the approximate validity of this picture. On a deeper level, however, the nucleon is a dynamic entity which should respond to its surroundings. The quenching of the inelastic electron-nuclear longitudinal response function $SL(q)$ (Ref. 1) and the EMC (European Muon Collaboration) effect[2] are recent examples which may indicate that the internal structure of the nucleon is appreciably altered by its surrounding nuclear environment. To explain these effects, several authors[1,3–5] have invoked an increase in the size of the nucleon within a nucleus over that in free space. An increase of 10–20 % (with perhaps a corresponding decrease in effective mass) has been suggested.

We note that K^+-nuclear scattering is another possibility for probing the effect of the nuclear medium upon the nucleon size.[6] To determine the usefulness of the K^+ for observing these unconventional [quantum chromodynamics (QCD) related] medium effects, we first assess the change in the K^+-nucleon amplitude due to an increase in the nucleon's size (Sec. II) and second show that we have a reliable method of calculating K^+-nuclear scattering once the elementary K^+-nucleon amplitude has been determined (Sec. III).

At low energies the K^+ interacts predominantly through the s wave with a small scattering length which, in the simple model of a hard sphere, suggests a short range interaction, quite sensitive to the size of the nucleon. In Sec. II we review a number of models which allow us to estimate this sensitivity. The models will also provide the off-shell range of the K^+-nucleon interaction, a quantity needed for a precise calculation of multiple scattering within the nucleus.

The K^+-nuclear total cross section is best suited to this study, since in this case the exact form of the nuclear body density is needed only for second and higher order scattering. As discussed in Sec. III, single scattering from the bound nucleons is dominant; conventional medium corrections are small and calculable for laboratory momenta in the range 300–800 MeV/c, and do not mask the less conventional ones related to nucleon size variations.

The central experimental observable in this analysis is the ratio of the K^+-nuclear ($N=Z$) to K^+-deuteron total cross section. This ratio will be largely free of experimental normalization uncertainties, and the errors due to inaccuracies in K^+-nucleon phase shifts employed in the theoretical analysis will cancel to first order.

The principal result of this work, described in detail in Sec. III, is summarized in Fig. 5. This figure compares our (conventional) calculation of the ratio of K^+-carbon to K^+-deuteron total cross sections with the available data. The main points of interest are (1) the calculation lies at least 2.5–3 standard deviations below the experimental data, and (2) an increase of the S_{11} K^+-nucleon phase shift by $\sim 15\%$, consistent with an increase of the confinement range of between 10% and 30%, produces agreement with experiment. It is clearly of great interest to obtain further total cross section data on light nuclei to test these ideas.

II. K^+-N AMPLITUDES AND NUCLEON SIZE

We will examine the assumption (along with the authors of Refs. 1 and 3–5) that the effect of the medium is to alter the radius and effective mass of the nucleon. A variety of models will be used to calculate the change in the S_{11} phase shift corresponding to a given change in the radius of the nucleon. Looking ahead, the results, summarized in Table I, indicate that for the models considered and at a laboratory momentum of 800 MeV/c a 10% increase in radius usually produces a 5–10 % increase in $\delta_{S_{11}}$; the effect is more pronounced at lower energies. We have neglected the variations of the smaller,

TABLE I. Variations in the S_{11} phase shift with model radius parameters. The line labeled Martin corresponds to the phase shift analysis of Ref. 12. The cloudy bag model is calculated only at the lower energy where it is applicable.

	r (fm)	a (fm)	δ_0 (200 MeV/c)	% increase	δ_0 (442 MeV/c)	% increase
Martin		-0.32	-0.325		-0.692	
Hard sphere	0.32	-0.32	-0.325		-0.718	
	0.352	-0.352	-0.357	10	-0.790	10
	0.384	-0.384	-0.390	20	0.862	20
Square well	0.55	-0.32	-0.31		-0.67	
$V_0=1080$ MeV	0.605	-0.34	-0.33	8	-0.71	7
	0.66	-0.36	-0.35	15	-0.75	12
	$\langle r^2\rangle^{1/2}$					
Bender and	0.67	-0.325	-0.327		-0.641	
Dosch	0.74	-0.359	-0.358	9.4	-0.671	4.6
(Ref. 7)	0.81	-0.392	-0.388	18.6	-0.690	10.7
	bag radius					
Cloudy bag	0.8	-0.32	-0.317			
(Ref. 9)						
($f=85$ MeV)	0.9	-0.335	-0.331	4		
	1.0	-0.35	-0.343	8		
Cloudy bag	1.0	-0.32	-0.313			
($f=95$ MeV)	1.1	-0.33	-0.319	2		

higher angular momentum partial waves with nucleon size.

The dominant S_{11} phase shift is negative (repulsive) and varies nearly linearly with the K^+-nucleon momentum $k_{\text{c.m.}}$ up to a laboratory momentum of about 0.8 GeV/c. Specifically, the approximation $\delta_{S_{11}}=ak_{\text{c.m.}}$ where $a=-0.32$ fm gives a good representation of the data in this region. Above this momentum the amplitude becomes inelastic and phase shift analyses disagree somewhat. The simplest potential which reproduces this behavior is a hard sphere with a radius $R=a$. If both nucleon and kaon grow proportionately when within the nucleus, we would expect R, and consequently the phase shift, to scale linearly with the increase of hadron sizes.

Softening of the hard sphere can account for the small deviations from the linear approximation. Without any systematic optimization we find that a (rectangular) barrier of height about 1080 MeV and radius 0.55 fm accurately reproduces the S_{11} phase shift up to a laboratory momentum of 0.8 GeV/c. We can inflate the hadron sizes as with the hard sphere model, however there is now some ambiguity as to how the potential height should change. If the barrier is very high in relation to the incident energy, the variation of the barrier height is not important as the sphere still remains hard. Consequently, the results of the preceding paragraph are reproduced. At higher energies any softening of the well would be seen as a decrease in magnitude of the phase shift tending to cancel the increase due to the radius increase. If we assume that the interaction is proportional to quark density, then, if the radius increases by a factor f, conservation of normalization requires that the potential height scale by $1/f^3$. For the barrier found above, the lowering of the magnitude of the phase shift due to the softening of the barrier partly cancels the increase due to the growth in the radius leaving us with a net increase in the magnitude of the phase shift of about 7% for a radius increase of 10%. To better assess the softening effect we now turn to two more detailed models which have appeared recently.

In the model of Bender and Dosch[7] the nucleon and kaon are represented by the commonly used models of constituent quarks bound by oscillator potentials. The kaon and nucleon interact through one-gluon exchange between quarks in each of the two hadrons. Quark interchange must also occur to return the color singlet nature of the hadrons. For normal free nucleon and kaon sizes and a strong fine structure constant of 0.67 both the $I=0$ and $I=1$ s-wave phase shifts obtained are in agreement with experiment. To estimate the effect of the nuclear medium we adjust the parameters of the model to give both the radius increase and effective mass decrease such as suggested by Noble.[1] This requires an increase of the oscillator radius parameter by a factor P and a decrease in the masses of the nonstrange constituent quarks by $1/P$. As a result of these changes all (nonstrange) hadron masses are lowered by $1/P$. The decrease in quark mass is exactly what one would predict from bag models in which the constituent quark mass is interpreted as the zero-point energy of massless "current" quarks. An increase in bag size leads to a decrease in the zero-point energy and hence of the effective mass. Reference 8 contains an improved version of this model which includes quark interchange and introduces a repulsive barrier to the potential in addition to the one gluon exchange potential already discussed. This added potential would be expected to further increase the phase shift change upon nucleon swelling from the value calculated with gluon exchange alone.

As a final model we consider the cloudy bag model[9] which reproduces the S_{11} phase shift quite well for low energies. The advantage of this model is that the parameters can be changed in a natural manner to simulate the nucleon swelling. The phase shift is solely a function of the bag radius R and the pion decay constant f_π if the bare quarks are taken massless. Thus when R is increased, f_π will remain constant because it is a parameter of the fundamental Lagrangian. The constituent quark mass, $\omega=2.04/R$, however, does decrease in a manner consistent with the previous model. The results of our calculation for two values of f_π are shown in Table I. They show that a 10% radius increase produces a 5% increase in the phase shift for momenta below 200 MeV/c. A calculation at 442 MeV/c is not presented as this is beyond the range of validity of the model.[9]

III. K$^+$-NUCLEAR SCATTERING

The K$^+$-nuclear scattering was calculated with a microscopic optical potential[10] which incorporates nucleon binding, recoil, and blocking with a three-body model of meson, struck nucleon, and core. The on-shell K$^+$-nucleon t matrix was constructed using Martin's phase shifts.[12] The off-shell range in momentum space, α, is related to the size of the K$^+$-nucleon system and was evaluated from the models described in Sec. II. The cloudy bag model predicts a value of about 600 MeV/c, while the other potential models predict approximately 900 MeV/c due to the smaller interaction range. As we have shown in Ref. 10, the effect of variation of α over this interval on the ^{12}C and ^{40}Ca calculations is very small in the angular region below the first minimum in the differential cross section. Higher order medium corrections arising from nucleon-nucleon correlations and other nuclear structure effects are even smaller and will be discussed later in this section.

The differential cross section for scattering from C and Ca employing this model are compared with experiment in Figs. 1 and 2. Also included are curves calculated with the S_{11} phase shift increased by 10% and 20%. These curves have been calculated using the same parameters as curves labeled a in Fig. 5. We have adjusted the nuclear body density so that when folded with the (now altered) electromagnetic form factor of the nucleon the measured charge density is recovered. This adjustment produces a much smaller effect in the cross section than the accompanying change in the phase shift. Note the greater enhancement in the forward direction for carbon than for calcium. This difference is a consequence of the different nuclear thickness compared to the kaon mean free path. There is a "shadowing" saturation of the single scattering for calcium, whose size is comparable to the mean free path, causing the forward differential cross section to be

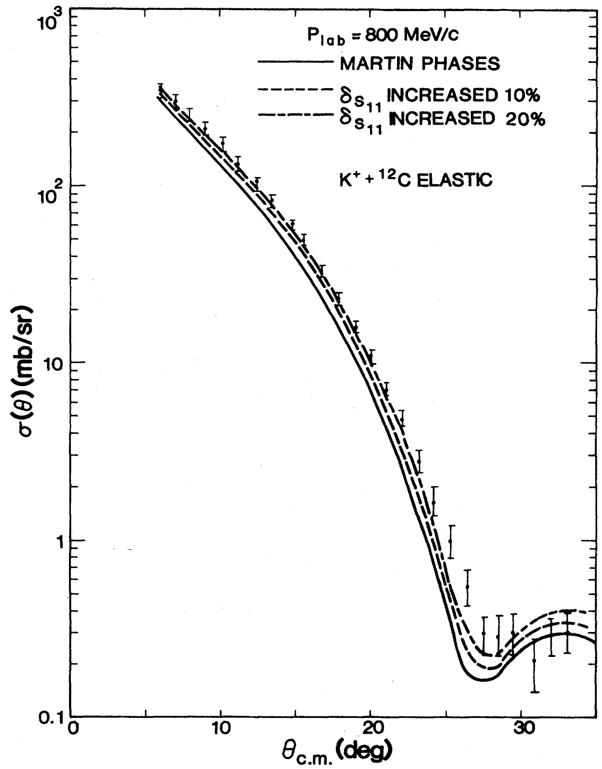

FIG. 1. K$^+$-C differential cross sections are plotted for $P_{lab}=800$ MeV/c to show the effect an increase in the S_{11} phase shift has on these measurements. The data are from Marlow *et al.* (Ref. 11).

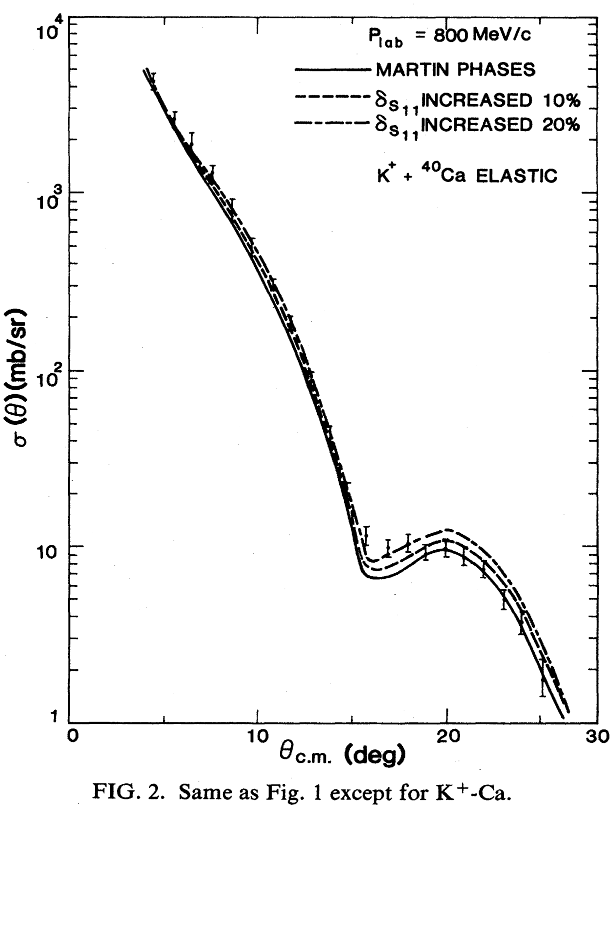

FIG. 2. Same as Fig. 1 except for K$^+$-Ca.

less sensitive to a change in nucleon area than in a smaller and hence more transparent nucleus.

To illustrate this effect we have, in Fig. 3, plotted the total cross section per nucleon versus a variable S_{11} phase shift. For this demonstration only, other K$^+$-nucleon phase shifts were taken to be zero, as were binding and other medium corrections. The single scattering approximation would result in $\sin^2\delta$ for all nuclei; deviations from this function are due to multiple scattering. The arrows indicate the actual phase shifts obtained by Martin[12] for the two momenta. At these values the increase of total cross section per nucleon for the same increase in the elementary phase shift is greater for C than for Ca. The slope is even smaller for a more massive nucleus. In addition, the Coulomb scattering is stronger for nuclei with high Z, tending, for small angle scattering, to mask any increase in the strong part of the phase shift. This greater sensitivity in smaller nuclei is to be balanced against the expectation that nucleon swelling is greater for larger nuclei.[4]

The enhancement of the cross section of C relative to the Ca obtained by the increase in the S_{11} phase shift is precisely what is needed to improve agreement with the data.[11] Suggestive as this observation is, the discrepancy may be largely a reflection of the uncertainty in the experimental normalization (18%) and the K$^+$-nucleon phase shifts.

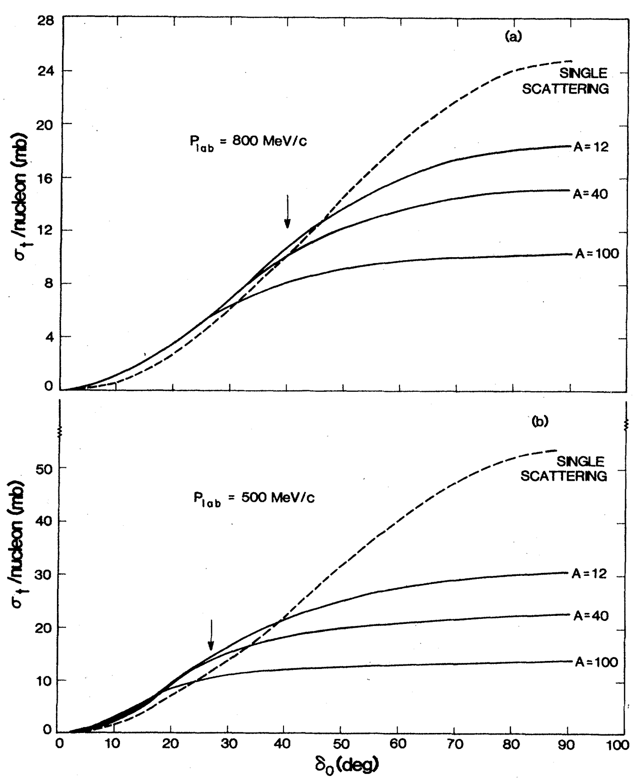

FIG. 3. The total cross section per nucleon is plotted vs s-wave phase shift for a laboratory momentum of 800 MeV/c and 500 MeV. The sensitivity of σ_t/nucleon to an increase in phase for different size nuclei is shown. The arrows indicate the values of $\delta_{S_{11}}$ (Martin) for the two energies.

A cleaner observable than the differential cross section, both on experimental and theoretical grounds, is the ratio, T, of the total cross sections of K$^+$-nuclear to K$^+$-deuteron scattering. The advantages of this ratio are as follows:

(1) Experimental uncertainties due to beam normalization tend to cancel in the ratio.

(2) The ratio T depends upon the nuclear form factor only through the second and higher multiple scattering terms, which will be seen to be small. In contrast, the differential cross section is roughly proportional to the form factor, whose extraction from electron scattering introduces uncertainties due to the lack of knowledge of neutron densities. Of course the possibility of using this feature to measure neutron densities is very strong.[13]

(3) Uncertainties due to the K$^+$-nucleon phase shifts also tend to cancel in the ratio T. For nuclei with $N=Z$ the cancellation is exact in the single scattering impulse approximation, hence the ratio T will be $A/2$ independent of phase shift analyses. Any deviation from this value is due to higher order scattering and medium corrections. *It is the one medium correction, the change in the range of the confinement, presumed to be negligible for the deuteron, that we seek here.*

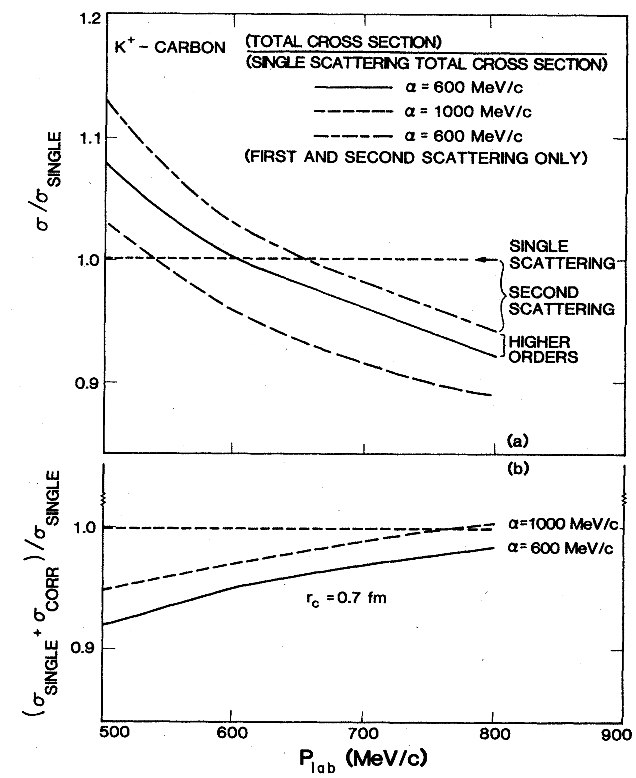

FIG. 4. (a) (σ_t carbon)/(σ_t carbon single scattering) is plotted as a function of laboratory momentum to show the contributions to the total cross section from double and higher order scattering in the expansion of the first order optical potential. (b) $(\sigma_{\text{single scattering}}+\sigma_{\text{correlation}})/\sigma_{\text{single scattering}}$ is plotted as a function of laboratory momentum to show the contribution to the total cross section due to correlations in the double scattering term.

In Fig. 4 the full multiple scattering solution and the sum of just the first and second scatters are plotted relative to the single scattering approximation. Single scattering is seen to account for at least 90% of the total cross section while another 8% is supplied by double scattering. The rapid convergence seen in Fig. 4 suggests that a diagrammatic approach to the calculation of the ratio T may be used for a multiple scattering expansion without resorting to an optical potential.

It is interesting to note that the double scattering contribution to the total cross section passes through zero at about 600—650 MeV/c. This can be understood by considering the contributions to this double scattering amplitude. Due to the high momenta involved, the pole piece (imaginary part) of the propagator dominates the principal value part in the integration over intermediate momenta. Thus the second scattering contribution to the total cross section is roughly proportional to $\mathrm{Re}(f(0)^2)$ where $f(0)$ is the isospin averaged K^+-nucleon forward scattering amplitude. For Martin's phase shifts this occurs at 580 MeV/c and different phase shift analyses will then just change the energy of this crossing point. Note that for nuclei with $N=Z$ the error in determining $f(0)$ is expected to be less than the individual isospin components since the analyses use data from K^+-deuteron scattering. A 10% decrease in $\delta_{S_{11}}$ results in an increase in the crossing momentum by 40 MeV/c. Nucleon-nucleon correlations with a correlation range of 0.7 fm lower the crossing point by an estimated further 60 MeV.

In a previous article[10] we have shown that nucleon binding, Pauli blocking, and recoil may be reliably computed; they lower the total cross section on carbon by 4% at a laboratory momentum of 800 MeV/c and by 5% at 500 MeV/c. If we wish to detect contributions to the total cross section due to nucleon size variations we must attempt to exhaust the more traditional ones. As a consequence we have examined several other possible contributors:

(1) The change in the total cross section due to the oblateness of ^{12}C (virtual excitation of the 2^+ state) was calculated in the second order impulse approximation and found to contribute less than 1.5% in the range 500—800 MeV/c. The deformation parameter was obtained from Ref. 14.

(2) The second order scattering due to nucleon-nucleon correlations was computed with a correlation function $1-\exp(-r/r_c)^2$ where the correlation range r_c is taken as 0.7 fm. The correction lowers the ratio T by 5% at 500 MeV/c decreasing to less than 2% near 800 MeV/c (see Fig. 5). The contribution decreases rapidly as r_c decreases.

(3) Double spin flip scattering was calculated in the second order impulse approximation and was found to contribute less than 0.1 percent to the total cross section.

(4) Relativistic off-shell corrections. The range of the off-shell t matrix as measured in the KN center of mass frame was evaluated within the models discussed in Sec. II. We have transformed the range into the K^+-nucleus system by both a nonrelativistic procedure[15] and a fully relativistic procedure[16] and find the difference between the two in the computed ratio T to be less than 1%.

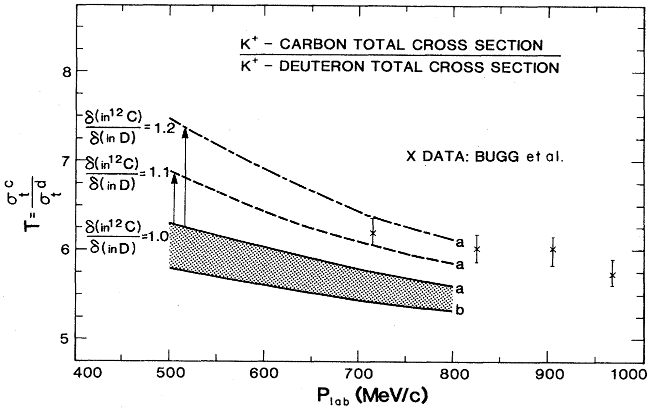

FIG. 5. (σ_t carbon)/(σ_t deuteron) is plotted as a function of laboratory momentum. The effect of increasing the S_{11} phase shift when the nucleon is in carbon is shown. Curve a corresponds to values $\alpha=600$ MeV/c and $r_c=0$ fm, while curve b to values $\alpha=900$ MeV/c, $r_c=0.7$ fm, contributions 1,2,6 included. The data are from Ref. 18.

(5) The nuclear density, previously extracted from electron scattering charge densities, was altered to a Gaussian form of the same rms radius. The difference is less than 1% in the calculation of T.

(6) Sequential double charge exchange,[17] $K^+n \rightarrow K^0p$ followed by $K^0p \rightarrow K^+n$ on a second nucleon, has also been included. In the double scattering approximation this process occurs only upon a correlated neutron-proton pair. The contribution to the total cross section is of the same sign and about 20% of the magnitude of the correction effect calculated in paragraph (2) above, lowering $\sigma_t(K^+\text{-C})$ by 2% at 500 MeV/c and by 0.5% at 800 MeV/c. The effect upon the K^+-C differential cross section of these two correlation effects is to cause a lowering of the first minimum by about 15% and of the second maximum by about 5%.

The shaded band in Fig. 5 gives our assessment of the theoretical uncertainties in the ratio T. The boundaries of the band have been determined by varying the parameters in the model (correlation length, off-shell range, etc.) in concert to minimize or maximize T. With the exception of nucleon binding corrections, the K^+-N free phase shifts have been used without the "swelling" effects described in Sec. II. The upper boundary curve a corresponds to values which maximize this ratio: $\alpha=600$ MeV/c, $r_c=0$, and no oblateness or double charge exchange. Lowering α to 300 MeV/c further increases T (although by less than 1%), however the models discussed in Sec. II imply that α is not less than 600 MeV/c. The lower boundary of the band, curve b, is obtained by using the parameters $\alpha=1000$ MeV/c, $r_c=0.7$ fm, and including both nuclear oblateness and double charge exchange.

The data of Bugg et al.,[18] also plotted in Fig. 5, are seen to lie 2.5—3 standard deviations above the band of uncertainty in the conventional calculation.

The discussion of Sec. II suggested that the S_{11} phase shift is increased when the nucleon is within a nucleus. Correspondingly, we have increased this phase shift by 10% and 20% in our calculation of the K^+-C total cross section. On the other hand, the calculation uses unaltered phase shifts for the K$^+$-deuteron calculation appropriate to its highly diffuse structure. The resulting ratio T has been plotted in Fig. 5. For clarity we have plotted only the curves corresponding to the conditions a which produced the upper boundary of the band. For other conditions the deviation from traditional calculations would be even greater.

A 10—15% increase in the S_{11} phase shift is seen to yield agreement between theoretical and the experimental values of the cross section ratio of carbon to deuterium.

IV. CONCLUSIONS

A measurement of the ratio of $T=\sigma(\mathrm{K}^+\text{-nucleus})/\sigma(\mathrm{K}^+\text{-deuteron})$ for $N=Z$ nuclei in the laboratory momentum range of 500—800 MeV/c provides an opportunity to observe medium effects related to nucleon expansion or deconfinement within the nuclear medium. Our major conclusions are as follows:

(1) An increase in the total cross section ratio T due to a 10% enhancement in the K$^+$-N S_{11} phase shift is larger than the uncertainties in the calculation of T due to traditional medium corrections. (See Fig. 5.)

(2) A 10—15% increase of the K$^+$-nucleon S_{11} phase shift produces agreement with the experimental total cross section ratio T.

(3) A 10—15% phase shift increase is also consistent with the differential cross section data on both ^{12}C and ^{40}Ca. (See Figs. 1 and 2.)

(4) Within several microscopic K$^+$-N models the apparent phase shift increase can be related to a nucleon size variation of a size consistent with current theoretical estimates based upon the EMC effect.

We would like to emphasize that although the comparison with the data is intriguing, the main point is that K$^+$-nucleus scattering can be treated sufficiently accurately in a multiple scattering picture to test our concepts of the degrees of freedom in nuclei.

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