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# $K^+$-nucleus scattering and the nucleon in the nuclear medium

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The $K^+$-nucleus interaction is investigated in the context of a covariant, momentum-space optical potential that incorporates covariant kinematics, relativistic normalizations, and phase-space factors, a covariant treatment of the recoil of the target nucleus, utilizes invariant amplitudes which are free of kinematic singularities, and allows an exact performance of the Fermi integration over the momentum of the struck nucleon. Elastic differential cross sections for $K^+$ scattering from $^{12}$C and $^{40}$Ca and total cross sections for $K^+$ scattering from $^{12}$C are calculated. An enhanced, in-medium, two-body interaction is indicated as the data is consistent with an approximate 30% enhancement of the theoretical calculations.

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Classical nuclear physics assumes that the properties of the nucleon are not altered when the nucleon finds itself in the nuclear medium. The success of classical nuclear physics demonstrates that to some degree this is so. However, as has been proposed in Refs. [1–5], there exists the possibility that the nucleon in the nuclear medium differs in a qualitative way from the free nucleon. To probe this possibility experimentally, a probe whose strong interaction with the nucleon is relatively weak has distinct advantages. The weaker the two-body interaction, the longer is the mean free path, $\lambda = 1/(\sigma\rho)$. The longer the mean free path, the deeper into the nucleus the probe can penetrate. This results in two desirable properties. First, modifications to the nucleon might well be expected to increase with increasing nuclear density. A probe which is able to penetrate into the nucleus would be probing nucleons in the region where these modifications would be largest. Second, the probe will be able to interact with all of the nucleons. This means that the nuclear cross section at high energies will be roughly $A$ times the two-body cross section. Thus, if the in-medium two-body cross section increases by a certain percent, the nucleus cross section will be enhanced by an equal percent. For more strongly interacting probes, the mean-free path is less than the nuclear radius. The interaction is thus surface dominated and is diffractive in character. The nuclear cross section is then approximately proportional to the sum of the squares of the nuclear radius and the radius of the projectile-nucleon interaction. An increase in the projectile-nucleon interaction for this case would only produce a small percentage change in the projectile-nucleus cross section.

There is also a theoretical advantage to working at high energies with a probe that interacts weakly—the conventional higher-order corrections to multiple scattering theory which are difficult to calculate become less important. From Ref. [6], the ratio of the strength of the second-order optical potential to the strength of the first-order optical potential is roughly given by

$$R = \sqrt{\sigma}\,\frac{l_c}{k}\rho \, , \tag{1}$$

where $\sigma$ is the projectile-nucleon total cross section, $k$ the incident momentum of the projectile, $l_c$ a correlation length, and $\rho$ the nuclear density. Thus we see that a weak two-body cross section $\sigma$ and a high energy (large $k$) will suppress the conventional second-order corrections which both removes theoretical uncertainties and also enhances the possibility of seeing less conventional mechanisms which would not necessarily be equally suppressed.

Of the strongly interacting probes, the $K^+$ has the weakest interaction with the nucleon, although high-energy pions are nearly as weak. Theoretical work on $K^+$-nucleus elastic scattering can be found in Refs. [5,7–9]. It was first shown in Ref. [8] that the experimental [10] $K^+$ elastic scattering cross sections from $^{12}$C were higher than the theory could predict. Similar results were found in Ref. [5], which led them to suggest that an increase of 15% in the $S_{11}$ phase shift (an increase of 26% in the two-body cross section) would resolve the discrepancy. In Ref. [9], it was suggested that this in-medium enhancement of the kaon-nucleon interaction might arise from enhanced meson clouds caused by the in-medium reduction of mesonic masses. Recent measurements [11] of the ratio of the total cross section of $K^+$ scattering from $^{12}$C to six times the scattering from the deuteron also indicate an enhanced in-medium kaon-nucleon cross section.

Here we examine the interaction of the kaon with a nucleus in the context of a covariant multiple scattering theory originally developed for the pion-nucleus interaction. In this theory, the first-order, impulse approximation to the optical potential is calculated without approximation in momentum space and used in a relativistic Schrödinger equation to generate elastic scattering differential cross sections and the total and the total reaction cross sections. The convergence parameter $R$ of Eq. (1) for a 450 MeV $K^+$ is quite small, $R = 0.02$ for a correlation length $l_c = 0.5$ fm. We thus expect the conventional higher-order corrections to be negligible and a careful treatment of the first-order optical potential to produce quantitative results. Some of the features which we incorporate into the theory and the calculation are (1) kinematics are treated [12] in a fully covariant manner, (2) invariant amplitudes [13,14] and invariant phase space and normalizations are used, (3) finite-range two-body scattering amplitudes are used and there is no limit on the number of two-body partial waves which can be incorporated, and (4) the Fermi-averaging integral over the momentum of the struck nucleon is performed exactly. The details of this formalism may be found in Ref. [13] and summaries may be found in Ref. [15].

To perform the calculation, we require an off-shell extrapolation of the kaon-nucleon amplitude. We choose a simple separable form for each spin, isospin channel $\alpha$,

$$\langle k'|t_\alpha(\omega)|k\rangle = \frac{v(k')}{v(k_0)}\langle k_0|t_\alpha(\omega)|k_0\rangle\frac{v(k)}{v(k_0)}\ . \qquad (2)$$

Any $t$ matrix, independent of the underlying physics, can be approximated [16] by such a separable form. For numerical convenience we choose a Gaussian form for $v(k), v(k)=\exp(-k^2/\beta^2)$. Calculated differential cross sections for the elastic scattering of $K^+$ from $^{12}$C and $^{40}$Ca at a laboratory momentum of 800 MeV/$c$ are given in Figs. 1 and 2 and compared with the data of Ref. [10]. The nuclear target wave functions are from Refs. [17,18]. In order to estimate the magnitude of the discrepancy between the theory and the data, we have scaled the theoretical calculations so that they fit the experimental cross section in the forward direction. We find a 33% adjustment is required for both $^{12}$C and $^{40}$Ca. This is in agreement with the original momentum-space calculations of Ref. [8].

The total cross section for $K^+$ scattering from $^{12}$C in the range $P_{\rm lab}=450$–$750$ MeV is pictured in Fig. 3 and compared with the data of Ref. [11]. Because the data are given as the ratio of the $^{12}$C total cross section to six times the deuteron cross section, we divide our calculated $^{12}$C cross sections by six times a smooth fit to the experimental [19] deuteron cross section. Here we find that we must scale the theoretical results by 25% to be in agreement with the data. Given that there is a systematic error of 17% for the differential cross section measurements of Ref. [10], the 25% increase for the total cross section is not inconsistent with the 33% increase needed for the differential cross section.

The question arises as to how model dependent is this discrepancy? We have checked the following dependences and found that in all cases we have less than one percent changes in the predicted cross sections. We may include the binding energy of the struck nucleon in calculating the energy at which the two-body amplitude is evaluated. This produces an effective energy shift of about 20 MeV, but as the kaon-nucleon amplitude is smooth over this energy range, such shifts do not matter. We vary the off-shell parameter $\beta$, which we expect to be near 1 GeV, from a value of 500 MeV to basically infinity and find negligible variation in the predicted cross sections. This is somewhat less sensitive than what was found in Ref. [8]. We have used the on-shell amplitudes of Arndt and co-workers [20]. We find that the older amplitudes of Martin [21] produce the same results. We have also calculated the second-order correlation corrections [22] for a short-range nucleon-nucleon repulsive

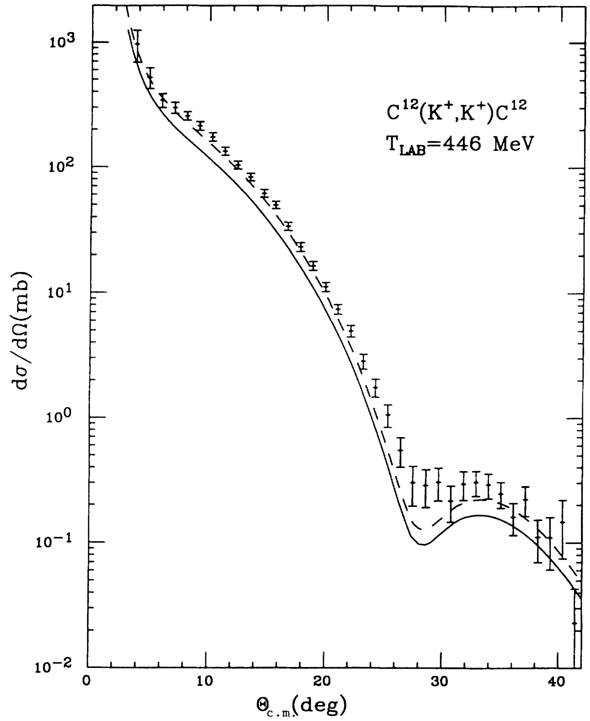

FIG. 1. The differential cross section for 800 MeV/$c$ $K^+$ elastic scattering from $^{12}$C. The data are from Ref. [10]. The solid curve is the theoretical prediction; the dashed curve is the theoretical prediction increased by 33%.

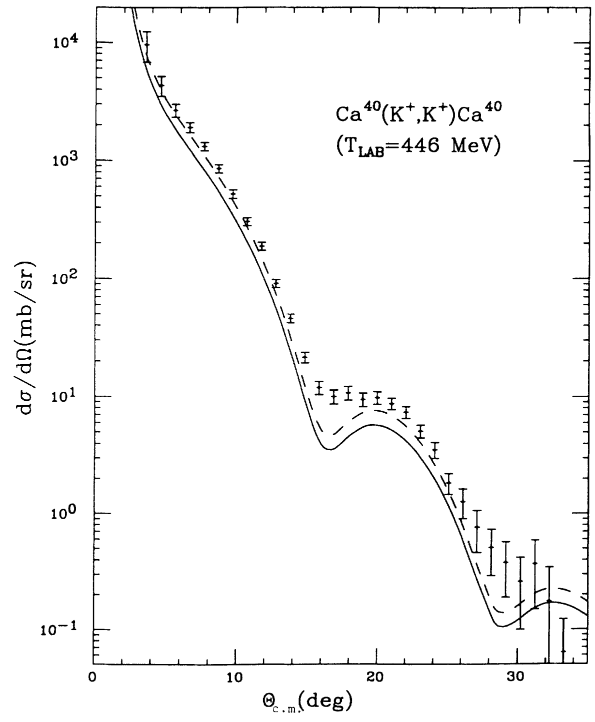

FIG. 2. The same as Fig. 1 except the target is $^{40}$Ca.

correlation and found that these are less than one percent corrections. In addition, the correlation corrections reduce the cross section and are thus of the wrong sign to account for the discrepancy. We have also added the kaon-nucleon *D* waves to the calculation and found that they do not contribute. This is all in agreement with Refs. [5,8]. We also note that the Born approximation in which we set the kaon-nucleus scattering amplitude directly equal to the optical potential is good to within several percent. Thus the second- and higher-order coherent scattering terms are only a couple percent of the single-scattering term. This sets a general scale for the double-scattering terms and indicates, but does not prove, that all conventional multiple-scattering corrections could not be much larger than a few percent. Finally, we note that the ratio of the $^{12}$C total cross section to six times the deuteron cross section is greater than one. The theory produces an answer which is slightly less than one, a simple consequence of shadowing. It is not impossible for conventional multiple-scattering theory to produce a result greater than one, but this requires a coherence between the scatterings from the individual nucleons which seems most unlikely, and certainly does not appear in the calculations, for the weak and repulsive two-body interaction and the short wavelength which we have for these high-energy kaons.

We ascribe no particular model [5,9] to the origin of this medium modification of the amplitude. The major conclusion here is that we corroborate at a qualitative level the results of Refs. [5,8]. At the quantitative level,

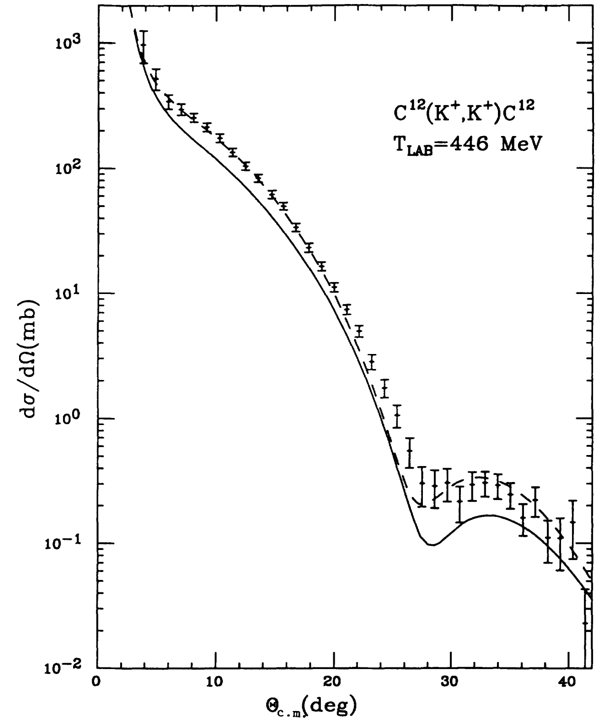

FIG. 4. The same as Fig. 1 except the dashed curve results from increasing the kaon-nucleon phase shifts by 25% (an increase in the two-body cross section by 36%).

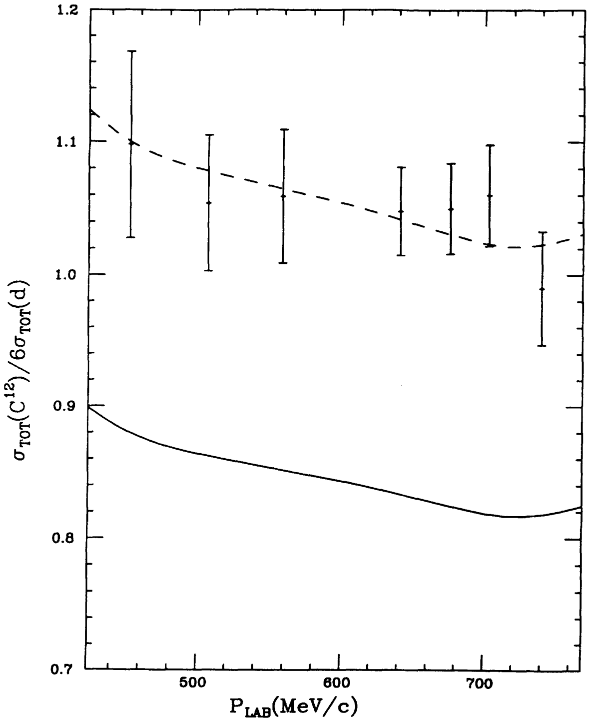

FIG. 3. Total cross section for $K^+$-$^{12}$C scattering as a function of the $K^+$ laboratory momentum. The data are from Ref. [11]. The solid curve is the theoretical prediction; the dashed curve is the theoretical prediction increased by 25%.

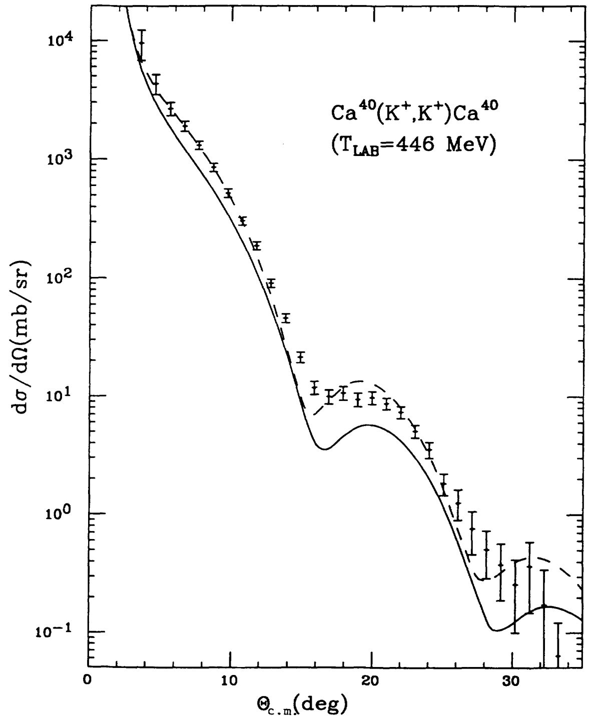

FIG. 5. The same as Fig. 2 except the dashed curve results from increasing the kaon-nucleon phase shifts by 42% (an increase in the two-body cross section by 64%).

we differ slightly from the results of Ref. [5]. Our 33% discrepancy for $^{12}$C is slightly larger than what was found for $^{12}$C in Ref. [5] and is roughly twice the discrepancy found there for $^{40}$Ca. Although we do not wish to ascribe any particular mechanism to account for the discrepancy we find, we will investigate the model of Ref. [5] in which the two-body phase shifts and hence the two-body cross sections are modified to fit the data. Here, we increase all the phase shifts by the same percentage until the theory fits the forward angle kaon-nucleus cross sections. We find that for $^{12}$C the phase shifts must be increased by 25% (an increase in the two-body total cross section of 36%) while for $^{40}$Ca the phase shifts must be increased by 42% (an increase in the two-body total cross section of 64%). These results are pictured in Figs. 4 and 5. The difference between $^{12}$C and $^{40}$Ca can easily be understood. We find a consistent 33% discrepancy for both nuclei. However, in order to increase the forward elastic scattering on $^{12}$C by 33% we find we have to increase the two-body cross section by 36%. These numbers match the observation from the total cross section calculation, Fig. 3, that the $K^+$ sees about 90% of the twelve nucleons in $^{12}$C. The shadowing effect is much greater in $^{40}$Ca where the mean-free path of the kaon is approximately the radius of $^{40}$Ca and thus many of the nucleons in $^{40}$Ca are shadowed behind other nucleons. To increase the $^{40}$Ca cross section by 33% we find that it takes a 64% increase in the two-body amplitude. In summary, we find that there is a consistent discrepancy between the theory and the data of about 30%.

With these limited data, it is not possible to provide sufficient constraints so as to uniquely determine the physical phenomena that underlie the discrepancy. More data, particularly elastic differential cross sections at several energies and for a set of targets, would be helpful. Data on $^4$He, which even though it is all surface is also exceptionally dense, and on a very heavy nucleus, could provide some insight into the $A$ dependence and maybe the density dependence of the missing physics. Moving to lower-energy $K^+$ would be desirable as the two-body cross section becomes even weaker. High-energy pions, as they can also penetrate reasonably far into the nucleus, should also be studied as the probe dependence of this effect could be most illuminating. Comparisons of $\pi^+$ and $\pi^-$ scattering from a series of isotopes, such as the Ca isotopes, together with charge-exchange data, would allow a study of the isospin dependence of the underlying physical mechanism.

[1] J. V. Noble, Phys. Rev. Lett. **46**, 412 (1981).

[2] T. Goldman and G. J. Stephenson, Jr., Phys. Lett. **146B**, 143 (1984).

[3] L. Celenza, A. Rosenthal, and C. Shakin, Brooklyn College of CUNY, Report 84/041/123 (1984).

[4] F. E. Close, R. L. Jaffe, R. G. Roberts, and G. G. Ross, Phys. Rev. D **31**, 1004 (1985).

[5] P. B. Siegel, W. B. Kaufmann, and W. R. Gibbs, Phys. Rev. C **30**, 1256 (1984); P. B. Siegel, W. B. Kaufmann, and W. R. Gibbs, *ibid.* **31**, 2184 (1985).

[6] D. J. Ernst, J. T. Londergan, G. A. Miller, and R. M. Thaler, Phys. Rev. C **16**, 537 (1977).

[7] C. B. Dover and G. E. Walker, Phys. Rev. C **19**, 1393 (1979); A. S. Rosenthal and F. Tabakin, *ibid.* **22**, 711 (1980); R. Cotanch and F. Tabakin, *ibid.* **15**, 1379 (1977); Y. Sakamoto, Y. Hatsuda, and M. Toyama, Lett. Nuovo Cimento **27**, 140 (1980).

[8] M. J. Paez and R. H. Landau, Phys. Rev. C **24**, 1190 (1981).

[9] G. E. Brown, C. B. Dover, P. B. Siegel, and W. Weise, Phys. Rev. Lett. **60**, 2723 (1988).

[10] D. Marlow, P. D. Barnes, N. J. Colella, S. A. Dytman, R. A. Einstein, R. Grace, F. Takeutchi, W. R. Wharton, S. Bart, D. Hancock, R. Hackenberg, E. Hungerford, W. Mayes, L. Pinsky, T. Williams, R. Chrien, H. Palevsky, and R. Sutter, Phys. Rev. C **25**, 2619 (1982).

[11] Y. Mardor, E. Piasetsky, J. Alster, D. Ashery, M. A. Moinester, A. I. Yavin, S. Bart, R. E. Chrien, P. H. Pile, R. J. Sutter, R. A. Krauss, J. C. Hiebert, R. L. Stearns, T. Kishimoto, R. R. Johnson, and R. Olshevsky, Phys. Rev. Lett. **65**, 2110 (1990); R. A. Krauss, Texas A&M University Ph.D. thesis (1991).

[12] D. J. Ernst and G. A. Miller, Phys. Rev. C **21**, 1472 (1980); D. L. Weiss and D. J. Ernst, *ibid.* **26**, 605 (1982); D. J. Ernst, G. A. Miller, and D. L. Weiss *ibid.* **27**, 2733 (1983); D. R. Giebink, *ibid.* **25**, 2133 (1982).

[13] D. R. Giebink and D. J. Ernst, Comput. Phys. Commun. **48**, 407 (1988).

[14] D. J. Ernst, G. E. Parnell, and C. Assad, Nucl. Phys. **A518**, 658 (1990); D. R. Giebink, Phys. Rev. C **32**, 502 (1985).

[15] M. B. Johnson and D. J. Ernst, Ann. Phys. (N.Y.) (to be published); D. J. Ernst, in *Pion-Nucleus Physics: Future Directions and New Facilities at LAMPF,* edited by R. J. Peterson and D. D. Strottman (American Institute of Physics, New York, 1988); in *Quarks, Mesons and Nuclei I: Strong Interactions,* edited by W-Y. P. Hwang and E. Henley (World Scientific, Singapore, 1989).

[16] D. J. Ernst, C. M. Shakin, and R. M. Thaler, Phys. Rev. C **8**, 46 (1973).

[17] M. Beiner, H. Flocard, N. Van Gai, and P. Quentin, Nucl. Phys. **A238**, 29 (1975).

[18] J. Negele, Phys. Rev. C **1**, 1260 (1970).

[19] D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. N. Wilson, J. D. Davies, J. D. Dowell, P. M. Hattersley, R. J. Homer, A. W. O'Dell, A. A. Carter, R. J. Tapper, and K. F. Riley, Phys. Rev. **168**, 1466 (1968); T. Bowen, P. K. Caldwell, F. N. Dikmen, E. W. Jenkins, R. M. Kalbach, D. V. Peterson, and A. E. Pifer, Phys. Rev. D **2**, 2599 (1970); T. Bowen, E. W. Jenkins, R. M. Kalbach, D. V. Peterson, A. E. Pifer, and P. K. Caldwell, *ibid.* **7**, 22 (1973).

[20] R. A. Arndt, L. D. Roper, and P. H. Steinberg, Phys. Rev. D **18**, 3278 (1978); R. A. Arndt and L. D. Roper, *ibid.* **31**, 2230 (1985).

[21] B. R. Martin, Nucl. Phys. **B94**, 413 (1975).

[22] C. M. Chen and D. J. Ernst, in progress.