K^+-Nucleus Scattering and the "Swelling" of Nucleons in Nuclei

G. E. Brown
State University of New York, Stony Brook, New York 11794

C. B. Dover
Brookhaven National Laboratory, Upton, New York 11973

P. B. Siegel
California State Polytechnic University, Pomona, California 91768

and

W. Weise
Institut für Theoretische Physik, Universität Regensburg, D-8400 Regensburg, Federal Republic of Germany
(Received 15 January 1988)

We investigate the utility of the K^+ meson as a probe of effective-size modifications ("swelling") of nucleons in the nuclear medium. The K^+-nucleus elastic and total cross sections are found to be sensitive to the density-dependent effective masses of the vector mesons (ρ,ω) whose exchange is responsible for the dominant part of the low-energy K^+-nucleon interaction. This density dependence is estimated in several ways and used to construct a K^+-nucleus optical potential. Such a model is consistent with the $K^+ + {}^{12}C$ data at 800 MeV/c, and provides a physical picture of the "swelling" mechanism in terms of the medium modifications of the meson cloud of the nucleon.

PACS numbers: 25.80.Nv, 21.65.+f

The European Muon Collaboration effect[1] suggests that the quark momentum distribution in a nucleon is modified in the nucleus. It is important to search for other processes which are sensitive to the subtle modifications of quark correlation functions in the nucleus, i.e., to the "swelling" of nucleons. The K^+ meson is a promising probe in this context,[2] since its interaction with nucleons is rather weak at low energy ($\sigma_{tot}^{K^+N} < 10$ mb for $p_L < 400$ MeV/c). Because of its long mean free path, the K^+ serves as a *volume* probe[3] of nuclei, and is sensitive to density-dependent "swelling" phenomena which are maximal in the nuclear interior. Strongly absorbed surface-localized particles (K^-, $\pi^\pm$, $\bar{p}$, etc.), on the other hand, incur large multiple-scattering corrections in nuclei, and these mask the rather delicate effects from nucleon "swelling."

Below 300 MeV/c, the K^+-nucleon interaction[4] is dominated by the isospin $I=1$ s-wave (S_{11}) amplitude. The phase shift $\delta(S_{11}) \approx -kR$, where $R \approx 0.32$ fm. Note that $R \approx 1/m_V$, where m_V is the vector-meson (ρ or ω) mass. In meson-exchange models of the K^+N interaction,[5] ρ and ω exchange plays a dominant role, since one-pion exchange is not allowed. In this respect, the K^+ interacts with a nucleon much as a virtual photon does, as illustrated in Figs. 1(a) and 1(b). The electromagnetic size $\langle r_{em}^2 \rangle^{1/2}$ of the nucleon is then determined partly by the vector-meson cloud and partly by the core size $\langle r_{core} \rangle^{1/2}$ according to the relation

$$\langle r_{em}^2 \rangle = 6/m_V^2 + \langle r_{core}^2 \rangle. \quad (1)$$

The effects of isoscalar two-pion exchange (the σ) can be largely accounted for by $KN \rightarrow KN$ "box diagrams" with K^*N, $K\Delta$, and $K^*\Delta$ intermediate states,[6] as shown in Figs. 1(c) and 1(d).

If one rescales to a value $R' \approx 1.1R$, one obtains a good fit to the elastic $K^+ + {}^{12}C$ scattering[7] at 800 MeV/c, as well as the ratio

$$R_T = \sigma_{tot}(K^+ + {}^{12}C)/6\sigma_{tot}(K^+ + d). \quad (2)$$

Siegel, Kaufmann, and Gibbs[2] attributed this rescaling

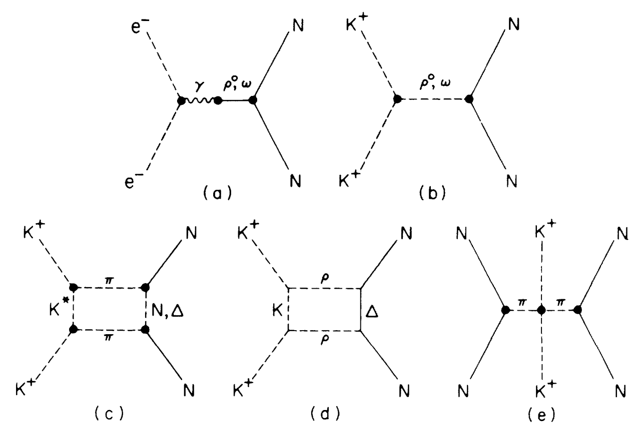

FIG. 1. (a),(b) The interaction of virtual photons and K^+ mesons with nucleons. (c),(d) Box diagrams which contribute to kaon-nucleon scattering. (e) An exchange-current effect due to $K\pi$ scattering.

to "partial deconfinement" of quarks. Here we present an alternative picture of the effective K^+N interaction in the nucleus in terms of the density-dependent masses $m_V(\rho)$ of the vector components of the nucleon meson cloud. (We assume $m_\omega = m_\rho = m_V$.) Our starting point is the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin (KSRF) relation,[8] which is assumed to hold not only in vacuum, but also in the nuclear medium of density ρ:

$$m_V^2(\rho) = 2f_\pi^2(\rho)g^2, \tag{3}$$

where $f_\pi(0)$ is the pion-decay constant in free space and g is a universal gauge coupling constant determined from the decay $\rho \to \pi\pi$. If we assume g to be density independent, then

$$m_V^2(\rho)/m_V^2(0) = f_\pi^2(\rho)/f_\pi^2(0). \tag{4}$$

We now consider several methods of estimating $f_\pi^2(\rho)/f_\pi^2(0)$. In the Nambu-Jona-Lasinio model,[9] explicit calculations[10,11] give

$$f_\pi(\rho)/f_\pi(0) = m_\sigma(\rho)/m_\sigma(0), \tag{5}$$

where m_σ is the mass associated with the scalar σ field:

$$m_\sigma(\rho) \approx 2m_Q(\rho). \tag{6}$$

The constituent quark mass $m_Q(\rho)$ is obtained by our solving the gap equation in the mean-field (Hartree) approximation. One finds[11] for $\rho \le \rho_0$

$$m_\sigma(\rho)/m_\sigma(0) \approx 1 - \tfrac{1}{2}\lambda\rho/\rho_0 \tag{7}$$

with $0.22 < \lambda < 0.54$. Whereas λ is model dependent, the mass of the σ must *decrease* towards the pion mass, since the σ and π become degenerate at the chiral restoration density.

A result very similar to Eq. (7) is also obtained[11] in the language of mesons and nucleons. Here, the decrease of $m_\sigma(\rho)$ with density follows from medium dependence in the constituent pion propagators which make up the effective σ exchange; specifically, from the introduction of isobar-particle, nucleon-hole insertions in the pion propagator. For $\frac{1}{3} < g'_{N\Delta} < 0.45$, where $g'_{N\Delta}$ is the local field correction[12] in pionic units, we obtain $0.2 < \lambda < 0.3$ in Eq. (7).

Another way to estimate the density dependence of vector-meson masses is to exploit the relationship of meson and nucleon masses $m_V(\rho)$ and $m_N(\rho)$ in the constituent quark model. Here $m_N(\rho) \approx 3m_Q(\rho)$ and $m_V(\rho)$ is somewhat larger than $2m_Q(\rho)$. Thus

$$\lambda \approx 2[1 - m_N(\rho_0)/m_N(0)]. \tag{8}$$

Using the phenomenological value[13] $m_N(\rho_0)/m_N(0) \approx 0.83\text{–}0.87$ we obtain $0.26 < \lambda < 0.34$, consistent with the above estimates.

Now consider the Born amplitude $f_{K^+N}(\rho)$ for K^+N scattering in a medium of density ρ through vector-meson exchange. From Eqs. (4), (5), and (7), we get

$$f_{K^+N}(\rho) \approx \frac{f_{K^+N}(0)}{(1-\lambda\rho/2\rho_0)^2}, \tag{9}$$

where we assume $q^2 \ll m_V^2$ in the meson propagator. From Eq. (9), we construct the K^+-nucleus optical potential $V_{\rm opt}^{K^+}(r)$:

$$V_{\rm opt}^{K^+}(r) = V_0^{K^+}\frac{\rho(r)/\rho_0}{1-\lambda\rho(r)/\rho_0} \approx \frac{\tilde{V}_0^{K^+}}{1+e^{(r-\tilde{R})/a}}, \tag{10}$$

where $V_0^{K^+} = (-2\pi/E_{K^+})f_{K^+N}(0)\rho_0$, E_{K^+} is the total K^+ energy, and $\tilde{V}_0^{K^+} = V_0^{K^+}/(1-\lambda)$. The effect of the nonlinear density dependence in Eq. (10) is seen to be an *increased repulsion* in the real potential and a *decreased effective radius* $\tilde{R} = R - \lambda a$ for the nucleus. This is precisely what is required in phenomenological fits[7,14] to $K^+ + {}^{12}C$ elastic-scattering data. A similar radius change occurs for pions,[15] because of the Lorentz-Lorenz effect, but in this case $\tilde{R} > R$.

To demonstrate the effect of the nonlinear density dependence in Eq. (10) on K^+ scattering, we have performed a series of optical model calculations of $K^+ + {}^{12}C$ elastic and total cross sections as a function of p_L. The calculations were actually done with a nonlocal version of Eq. (10), following Siege, Kaufmann, and Gibbs.[14] We included the Coulomb potential corresponding to a realistic charge density in the calculation of $d\sigma/d\Omega$. The hadronic density was taken to be a Fermi form $\rho(r) = \rho_0/\{1+\exp[(r-R)/a]\}$ with $R = 2.274$ fm and $a = 0.398$ fm. These parameters were adjusted to fit electron-scattering data on ${}^{12}C$, with our taking into account finite nucleon size. Angle transformations and off-shell form factors were also included.[14,16] We included the elementary s-, p-, d-, and f-wave K^+N amplitudes of Martin.[17] Paez and Landau[16] and Siegel, Kaufmann, and Gibbs[14] have studied in detail the dependence of $K^+ + {}^{12}C$ elastic scattering on changes in form factors, K^+N amplitudes, etc. These changes are modest, and none of the existing calculations involving a K^+ potential linear in $\rho(r)$ succeeds in reproducing the data. We note that the theoretical uncertainties[2] in R_T are considerably smaller than the change induced by the nonlinear density dependence of $V_{\rm opt}^{K^+}$.

The results for the elastic angular distribution at $p_L = 800$ MeV/c are shown in Fig. 2(a) for $\lambda = 0$ and 0.2. The choice $\lambda = 0.2$ provides a good fit to the data, whereas the choice $\lambda = 0$ (free K^+N amplitudes) falls short. In Fig. 2(b), we show the p_L dependence of the total cross-section ratio R_T of Eq. (2), compared with the data of Bugg *et al.*[18] Again, the fit with $\lambda = 0.2$ is adequate, whereas for $\lambda = 0$ one predicts "shadowing" for $p_L > 600$ MeV/c (i.e, $R_T < 1$). The data do not show this effect below 1 GeV/c. Note that for $K^+ + {}^{40}Ca$ at 800 MeV/c (not shown), we obtain only modest changes in elastic cross section with λ, in agreement with the calculations of Ref. 2. Thus, the light nuclei provide the

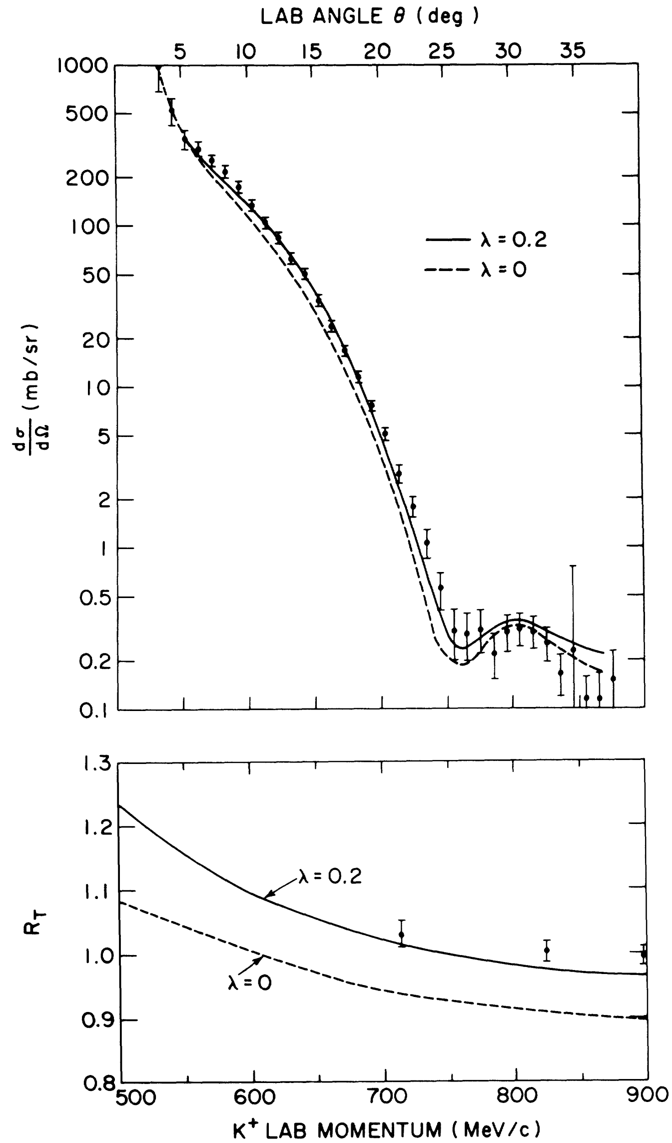

FIG. 2. The angular distribution for $K^+ + {}^{12}C$ elastic scattering at 800 MeV/c is shown at the top. The data are taken from Marlow *et al.* (Ref. 7). The dashed and solid curves correspond to optical-model calculations, following the methods of Ref. 14, for $\lambda = 0$ or 0.2, respectively. At the bottom is shown the total cross-section ratio R_T of Eq. (2) as a function of p_L, for $\lambda = 0$ and 0.2. The data are from Bugg *et al.* (Ref. 18).

optimum sensitivity to deviations from the "$t\rho$" approximation for $V_{\rm opt}^{K^+}$.

The optimum choice $\lambda = 0.2$ used in Fig. 2 is a bit below the range of values given by Eqs. (7) and (8). This may imply that the mass $m_V(\rho)$ has a less pronounced density dependence than $m_\sigma(\rho)$, as suggested by Bernard and Meissner.[19]

In our approach, the energy dependence of $V_{\rm opt}^{K^+}$ is carried by the free-space amplitude $f_{K^+N}(0)/E_{K^+}$, i.e., λ is independent of energy. One then predicts an increasing amount of "antishadowing" ($R_T > 1$) below $p_L = 750$ MeV/c, as shown in Fig. 2(b). However, there are other sources of energy dependence in $V_{\rm opt}^{K^+}$ which could alter the picture, namely (i) renormalization of the "box diagrams" [Figs. 1(c) and 1(d)] in the medium and (ii) "exchange current" contributions in which the K^+ hits a pion [Fig. 1(e)]. Both of these yield energy-dependent corrections of order $\rho^2(r)$ to $V_{\rm opt}^{K^+}$. The latter is of order $\kappa f_{K\pi}\rho^2(r)/\rho_0 E_{K^+}$, where $\kappa \approx 0.1$ is the usual "wound integral," and $f_{K\pi}$ is the off-shell $K\pi$ amplitude. Quantitative estimates of (i) and (ii) are being developed.

In the preceding discussion, we have assumed that the ρ- and ω-exchange contributions to f_{K^+N} are subject to the same density-dependent renormalization. Note that $K^+ + {}^{12}C$ elastic scattering involves the isospin-averaged K^+N amplitude, so that the ρ cancels out in Born approximation, and only ω enters. Both the ρ and ω contribute in first order, however, to $(K^+, K^{+\prime}N)$ quasifree scattering, which constitutes the bulk of the total cross section at 800 MeV/c. In the (K^+, K^0) charge-exchange process, on the other hand, only the ρ contributes in first order. Experimentally, separate measurements of K^+ elastic, charge-exchange, and total-reaction cross sections on light targets as functions of p_L would be an invaluable aid to disentangling the isospin structure of the process and the reaction mechanism. Some new measurements of R_T have recently been made.[20] Data below 500 MeV/c would be particularly welcome, since here one enters the region of s-wave dominance of the K^+N amplitude, and a simple picture in terms of a density-dependent effective hard-sphere radius makes sense. The picture above 600 MeV/c is complicated by the formation of possible Z^* resonances[4] in K^+N partial waves with $l \neq 0$. The $K^+ + {}^4He$ system also represents an interesting case for experimental study, since here the central density ρ_0 is higher than that of ordinary nuclear matter, and hence the nucleon "swelling" effects may be amplified.

In summary, the apparent "swelling" of the nucleon needed to explain K^+-nucleus scattering can be understood in terms of a density dependence of the vector-meson masses $m_V(\rho)$ which enter into the K^+-nucleon interaction. The density dependence has been estimated by our relating $m_V(\rho)$ to the effective nucleon mass $m_N(\rho)$, or by our assuming that the KSRF relation holds in the nuclear medium. The discrepancy between first-order "$t\rho$" calculations and the observed $K^+ + {}^{12}C$ elastic angular distribution and total cross section is naturally explained in terms of an *increased* K^+N effective range arising from the *decrease* of the vector-meson mass in the nucleus.

This work was supported in part by the U.S. Department of Energy under Contracts No. DE-AC02-76ER13001 and No. DE-AC02-76CH00016 and by Bundesministerium für Forschung und Technologie Grant No. MEP 0234REA.

[1]J. J. Aubert *et al.* (European Muon Collaboration), Phys. Lett. **123B**, 275 (1983); A. Bodek *et al.*, Phys. Rev. Lett. **50**, 1431 (1983), and **51**, 534 (1983); for a recent review, see E. L. Berger, Argonne National Laboratory Report No. ANL-HEP-CP-86-103, 1986 (unpublished).
[2]P. B. Siegel, W. B. Kaufmann, and W. R. Gibbs, Phys. Rev. C **31**, 2184 (1985).
[3]C. B. Dover and P. J. Moffa, Phys. Rev. C **16**, 1087 (1977).
[4]C. B. Dover and G. E. Walker, Phys. Rep. **89**, 1 (1982).
[5]J. W. Alcock, W. N. Cottingham, and A. C. Davis, J. Phys. G **4**, 323 (1978).
[6]R. Büttgen, K. Holinde, and J. Speth, Phys. Lett. **163B**, 305 (1985).
[7]D. Marlow *et al.*, Phys. Rev. C **25**, 2619 (1982).
[8]K. Kawarabayashi and M. Suzuki, Phys. Rev. Lett. **16**, 255 (1966); Riazuddin and Fayyazuddin, Phys. Rev. **147**, 1071 (1966).
[9]Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961), and **124**, 246 (1961).
[10]V. Bernard, U.-G. Meissner, and I. Zahed, Phys. Rev. Lett. **59**, 966 (1987).
[11]T. L. Ainsworth, G. E. Brown, M. Prakash, and W. Weise, Phys. Lett. B **200**, 413 (1988); G. E. Brown, Prog. Theor. Phys. Suppl. **91**, 85 (1987).
[12]A. Arima, T. Cheon, K. Shimizu, H. Hyuga, and T. Suzuki, Phys. Lett. **122B**, 126 (1983).
[13]C. Mahaux and R. Sartor, Nucl. Phys. **A475**, 247 (1987); C. H. Johnson, D. J. Horen, and C. Mahaux, Phys. Rev. C **36**, 2252 (1987).
[14]P. B. Siegel, W. B. Kaufmann, and W. R. Gibbs, Phys. Rev. C **30**, 1256 (1984).
[15]W. R. Gibbs, B. F. Gibson, and G. J. Stephenson, Phys. Rev. Lett. **39**, 1316 (1977).
[16]M. J. Paez and R. H. Landau, Phys. Rev. C **24**, 1120 (1981).
[17]B. R. Martin, Nucl. Phys. **B94**, 413 (1975).
[18]D. V. Bugg *et al.*, Phys. Rev. **168**, 1466 (1968).
[19]V. Bernard and U.-G. Meissner, MIT Report No. CTP 1581, 1988 (to be published).
[20]E. Piasetsky and R. E. Chrien, private communication.