Scattering of K^+ Mesons by Nucleons*

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(Received January 2, 1958)

A calculation of the scattering of low-energy ($\lesssim 50$ Mev) K^+ mesons by nucleons via the mechanism of a boson-boson interaction between two pions and two K mesons is presented. The following experimentally observed features of the low-energy scattering seem to be simply represented by the scheme: (*a*) The scattering is predominantly in the S wave and the cross section shows a slight rise with increasing energy. (*b*) The effective nuclear potential is repulsive and of relatively short range ($\sim 1/2\mu$). (*c*) The charge exchange scattering is very small at very low energies. A preliminary discussion of the scattering at higher energies is given by introducing, in addition, the "direct" scattering via the interactions of K mesons with nucleons and hyperons.

INTRODUCTION AND SUMMARY OF RESULTS

THE scattering of K^+ mesons by nucleons has been and is being investigated experimentally by a number of groups.[1–4] At present several features of the existing experimental analyses are of particular interest insofar as they may serve as the basis for a preliminary theoretical study of K^+-nucleon scattering. We enumerate briefly those features, which we consider significant for our present theoretical analysis: (*a*) the magnitude of the K^+-hydrogen scattering cross section at very low energies ($\lesssim 50$ Mev), (*b*) the very gradual rise of this cross section in the energy interval from 0 to 200 Mev,[2] (*c*) the apparent constructive interference between the Coulomb and the nuclear scattering amplitudes in the K^+-proton differential cross section at small angles,[1,2] (*d*) the apparent variation in the ratio of the charge-exchange scattering to the non-charge-exchange scattering from a value of less than 1/10 at energies below 60 Mev to a value of about 0.24 at energies above 150 Mev.[1,2] Although these features are in evidence in the present experimental results, they are yet to be either confirmed or altered by the greatly improved statistics of the current and future experimental studies.

In this paper we shall discuss the results of the application of a simple theoretical scheme to the K^+-nucleon scattering problem. In particular we shall see to what extent the features of the scattering enumerated above can be reproduced within the framework of this scheme.

Our discussion of the scattering at very low energies will be based upon a mechanism recently suggested by the author.[5] The K meson is considered to be scattered via the exchange of two pions between the nucleon and the K meson. The scattering is then evaluated in terms of the pion-nucleon coupling constant (as given in the work of Chew and Low[6]) and the coupling constant which characterizes the interaction between two K mesons and two pions. As a result of the analysis we shall find that with the latter number taken as unity we obtain a repulsive nuclear potential (this is not dependent on the K-meson parity) and a zero-energy nuclear scattering cross section of about 5.3 mb. This cross section increases slowly with increasing energy. With the inclusion of the Coulomb scattering amplitude we estimate in Born approximation the differential cross section at 30 Mev.

Whereas a reasonably coherent treatment of the low-energy scattering via the above mechanism is given below, we are unable to do the same for the scattering above 100 Mev. Here we must deal with the fact that the continued very slow variation of the cross section with energy may indicate that the S-wave scattering is still predominant and also the fact of the increased charge-exchange scattering. The mechanism discussed above gives no charge-exchange scattering. We therefore introduce, in addition, the scattering via the direct interaction of K mesons, hyperons, and nucleons. By considering the scattering of pseudoscalar K mesons in the S wave via the intermediate pair state, in conjunction with the scattering via the exchange of pions, we obtain, at 100 Mev available kinetic energy in the center-of-mass system, the following cross sections:

$$\sigma(K^+ + p \rightarrow K^+ + p) \sim 17 \text{ mb},$$
$$\sigma(K^+ + n \rightarrow K^+ + n) \sim 3 \text{ mb},$$
$$\sigma(K^+ + n \rightarrow K^0 + p) \sim 6 \text{ mb}.$$

The charge-exchange to non-charge-exchange ratio is then about 0.3. The couplings of K mesons to nucleons and Λ particles and to nucleons and Σ particles are taken as $g_{K\Lambda N}^2/4\pi \sim 4$ and $g_{K\Sigma N}^2/4\pi \sim 0.4$. The analysis suggests that the coupling parameters which characterize the K meson-hyperon-nucleon interactions as well as that which characterizes the hypothesized four-field boson-boson interaction are "strong" couplings, but are not necessarily as large as the pion-nucleon

* Under the auspices of the U. S. Atomic Energy Commission.
† A National Science Foundation Postdoctoral Fellow.
[1] Hoang, Kaplon, and Cester, Phys. Rev. **107**, 1698 (1957).
[2] Lannutti, Goldhaber, Goldhaber, Chupp, Giambuzzi, Marchi, Quarini, and Wataghin, Phys. Rev. **109**, 2133 (1958). This work and reference 3 contain many further references.
[3] B. Sechi Zorn and G. T. Zorn, Phys. Rev. **108**, 1098 (1957).
[4] Meyer, Perl, and Glaser, Phys. Rev. **107**, 279 (1957).
[5] Saul Barshay, Phys. Rev. **109**, 2160 (1958).
[6] G. F. Chew and F. E. Low, Phys. Rev. **101**, 1570, 1579 (1956).

parameter, $g^2/4\pi \sim 15$. At the higher energies the scheme is, at present, nothing but phenomenology in that we supplement the pion exchange mechanism with the "direct" scattering by putting the latter into the scattering amplitude without an understanding of how its effect is damped at the lower energies. The form of the "direct" scattering which we introduce provides a simple way of correlating the three K^+-nucleon cross sections at about 160 Mev laboratory kinetic energy and is suggestive of the magnitude of the couplings involved. A treatment of this scattering will have to be done with methods better capable of handling the strong coupling of a heavy meson to baryons, when the parity of the K meson has been established by experiment.

In the next section we outline the method of calculation and give the relevant formulas. In our concluding remarks we give certain additional calculational results and summarize the discussion.

CALCULATION

We consider the scattering of K^+ mesons below 50 Mev. The scattering is assumed to proceed through the exchange of pions. The pion-nucleon interaction Hamiltonian is given in the papers of Chew and Low[6] and Miyazawa.[7] The interaction between K mesons and pions is taken to be

$$\lambda K_\alpha^\dagger K_\alpha \pi_j^\dagger \pi_j,$$

where the symbol for the particle denotes the field operator which destroys it, the isotopic spin indices α and j run from 1 to 2 and 3, respectively, and the dagger (†) denotes Hermitian adjoint. The S matrix for the scattering process to lowest order in λ is given in the center-of-mass system by

$$\begin{aligned} S_{if} &= \langle^{(-)}\mathbf{k}'|\mathbf{k}^{(+)}\rangle \\ &= 2\pi\delta(\omega'-\omega)\left\langle 0\left|\lambda\int d^3r\, e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}} \sum_{p,p'} \rho\{a_p a_{p'} e^{i(\mathbf{p}+\mathbf{p}')\cdot\mathbf{r}} + a_p^\dagger a_{p'}^\dagger e^{-i(\mathbf{p}+\mathbf{p}')\cdot\mathbf{r}} + a_p^\dagger a_{p'} e^{-i(\mathbf{p}-\mathbf{p}')\cdot\mathbf{r}}\right.\right. \\ &\qquad \left.\left. + a_p a_{p'}^\dagger e^{-i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{r}}\}\right|0\right\rangle \qquad (1) \\ &= (2\pi)^4\delta(\omega'-\omega)\sum_{p,p'}\rho\{\delta(-\mathbf{k}'+\mathbf{p}+\mathbf{p}'+\mathbf{k})\langle 0|a_p a_{p'}|0\rangle + \delta(-\mathbf{k}'-\mathbf{p}-\mathbf{p}'+\mathbf{k})\langle 0|a_p^\dagger a_{p'}^\dagger|0\rangle \\ &\qquad + (-\mathbf{k}'-\mathbf{p}+\mathbf{p}'+\mathbf{k})\langle 0|a_p^\dagger a_{p'}|0\rangle + (-\mathbf{k}'-\mathbf{p}'+\mathbf{p}+\mathbf{k})\langle 0|a_p a_{p'}^\dagger|0\rangle\}. \end{aligned}$$

The a_p and $a_p^\dagger$ are plane-wave pion annihilation and creation operators, respectively; the indices p and p' include the momentum and isotopic spin labels; the state $|0\rangle$ denotes the physical nucleon; and $\rho = -i(16\omega\omega'\nu\nu')^{-\frac{1}{2}}$ where $\omega = (\mathbf{k}^2+m_K^2)^{\frac{1}{2}}$, $\omega' = (\mathbf{k}'^2+m_K^2)^{\frac{1}{2}}$, $\nu = (\mathbf{p}^2+\mu^2)^{\frac{1}{2}}$, and $\nu' = (\mathbf{p}'^2+\mu^2)^{\frac{1}{2}}$ with μ = pion mass and m_K = K-meson mass. The expression may now be transformed by using the standard techniques of the Wick-Chew-Low field theory[6–8] for handling expressions like $\langle 0|a_p a_{p'}|0\rangle$. The t matrix given by $S_{if} = 1 - 2\pi i\delta(\omega'-\omega)t_{if}$ is then expressible in terms of the pion-nucleon interaction cross section. The result for the t matrix for zero momentum transfer ($\mathbf{k}'-\mathbf{k}=0$) is

$$\begin{aligned} \langle\omega'|t|\omega\rangle &= \frac{\lambda}{2(\omega\omega')^{\frac{1}{2}}}\left\{\int\left(\frac{f}{\mu}\right)^2\left(\frac{3p^4}{2\pi^2\nu^4}\right)dp + \frac{1}{12\pi^3}\int dp\int dq[4\sigma^{33}(q)+2\sigma^{13}(q)+2\sigma^{31}(q)+\sigma^{11}(q)]\right. \\ &\qquad \left.\times\left[\frac{p^4}{\nu^3\omega_q(\nu+\omega_q)}+\frac{p^4}{\nu^2\omega_q(\nu+\omega_q)^2}\right]\right\} \\ &\cong \frac{\lambda}{2(\omega'\omega)^{\frac{1}{2}}}\left\{\int\left(\frac{f}{\mu}\right)^2\left(\frac{3p^4}{2\pi^2\nu^4}\right)dp + \frac{1}{12\pi^3}\int dp\int dq\, 4\sigma^{33}(q)\frac{p^4}{\nu^2\omega_q(\nu+\omega_q)}\left[\frac{1}{\nu}+\frac{1}{\nu+\omega_q}\right]\right\} \\ &= \alpha/(\omega\omega')^{\frac{1}{2}}. \end{aligned} \qquad (2)$$

This expression gives the transition matrix for zero momentum transfer for K^+ mesons on protons or neutrons. There is no "spin flip" in either ordinary or isotopic space. The first term in the curly brackets is the Born approximation expressed in terms of the rationalized, renormalized pion-nucleon coupling constant, $f^2 = 4\pi(0.08)$; the second term involving an integral over the pion-nucleon cross sections σ^{ij} in the spin, isotopic spin states $(2j,2i)$ involves corrections from the multiple scattering of the exchanged pions on the physical nucleon. The momentum integrals are taken from 0 to $K_{\max} = (24)^{\frac{1}{2}}\mu$, i.e., the cutoff in our work is chosen at $5\,\mu$. Integrals of the above form have been evaluated in the work of Miyazawa[7] on the

[7] H. Miyazawa, Phys. Rev. **101**, 1564 (1956).
[8] G. C. Wick, Revs. Modern Phys. **27**, 339 (1955).

nucleon anomalous moments. We find for α

$$\alpha=(0.75/\mu)(\lambda/2). \tag{3}$$

The Born approximation contributes $(0.51/\mu)(\lambda/2)$ to α, and the terms involving the integrals over the pion-nucleon cross sections contribute $(0.24/\mu)(\lambda/2)$.

In order to take into account some higher order effects in the coupling λ, we propose to iterate the t matrix evaluated above in a "ladder" approximation. We define the complete T matrix for forward scattering to be the solution of the familiar equation[9]

$$\langle\omega'|T|\omega\rangle=\langle\omega'|t|\omega\rangle+\langle\omega'|t|\omega''\rangle(\omega-\omega''+i\eta)^{-1}\langle\omega''|T|\omega\rangle. \tag{4}$$

The type of diagrams included in this approximation are shown in Fig. 1. For a t matrix factorable in ω and ω' as given by Eq. (4), the exact solution for $\langle\omega'|T|\omega\rangle$ is given (with $k=k'$) by[10]

$$\langle\omega|T|\omega\rangle=\frac{\langle\omega|t|\omega\rangle}{1-\langle\omega|t|\omega\rangle^{-1}\int\dfrac{k'^2dk'\langle\omega|t|\omega'\rangle\langle\omega'|t|\omega\rangle}{2\pi^2(\omega-\omega'+i\eta)}}, \tag{5}$$

Now the total cross section is related to the imaginary part of $\langle\omega|T|\omega\rangle$ by

$$\sigma=-(2\omega/k)\,\mathrm{Im}\langle\omega|T|\omega\rangle. \tag{6}$$

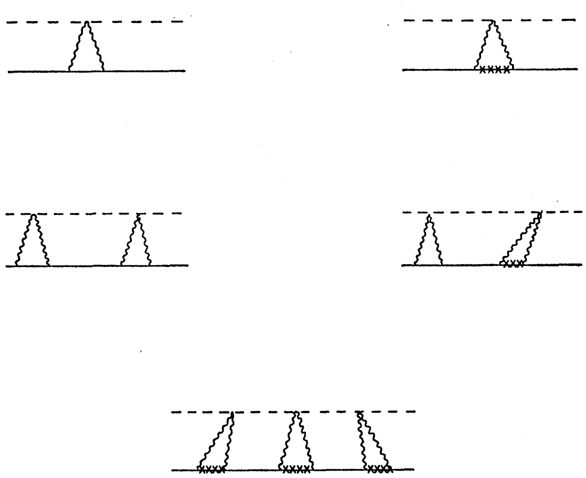

FIG. 1. Typical Feynman graphs considered in the calculation of the low-energy K^+-nucleon scattering via the mechanism of the boson-boson interaction between two pions and two K mesons.

[9] An equation of the form

$$\langle\mathbf{k}'|T|\mathbf{k}\rangle=\langle k'|t|k\rangle+\langle\mathbf{k}'|t|\mathbf{k}''\rangle\langle\mathbf{k}''|T|\mathbf{k}\rangle$$

was utilized in the early work of Chew on the pion-nucleon scattering problem [G. F. Chew, Phys. Rev. **94**, 1755 (1954)]. Equation (4) is obtained with $\mathbf{k}'=\mathbf{k}$ by neglecting the dependence of the integral term upon $\mathbf{\Delta}'=\mathbf{k}''-\mathbf{k}$. This is a first approximation and will give us an idea of the behavior of this scattering mechanism in this "ladder" approximation.

[10] J. S. Blair, Phys. Rev. **95**, 209 (1954).

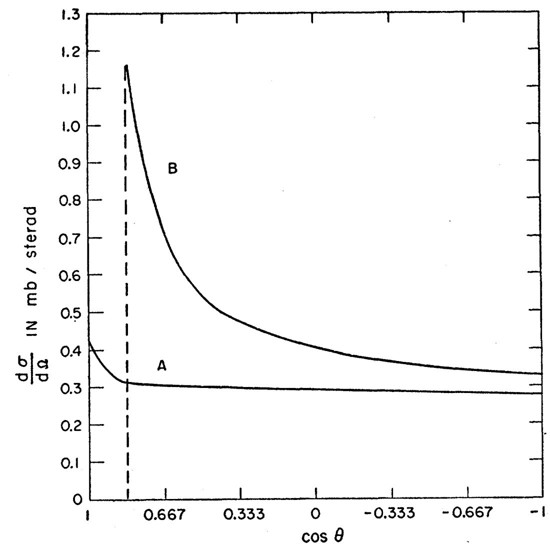

FIG. 2. Curve A—the center-of-mass differential cross section from the nuclear scattering of K^+ mesons by nucleons at 30 Mev K^+ kinetic energy in the laboratory. Curve B—the center-of-mass differential cross section from the combined nuclear and Coulomb scattering at this energy. The cutoff angle is taken at about 33°.

We thus obtain

$$\sigma=\frac{\lambda^2\alpha^2/\pi^2}{(1-D)^2+\lambda^2k^2\alpha^2/4\pi^2}, \tag{7}$$

where

$$D=-(\lambda\alpha/2\pi^2)P\int k'd\omega'/(\omega'-\omega),$$

and P denotes the principal value. Evaluation of this expression with $\lambda^2/4\pi\sim1$ gives a zero-energy cross section for the nuclear scattering of K^+-mesons on protons or neutrons of about 5.3 mb. If $\lambda^2/4\pi\sim5$, this cross section is about 14 mb. We see that the quantity D is negative and decreases somewhat with increasing ω. The cross section for the nuclear scattering from this mechanism alone consequently increases somewhat with increasing energy. For $\lambda^2/4\pi\sim1$ and $\omega-m_K\sim100$ Mev (identified as the available kinetic energy in the center-of-mass system in this static treatment of the nucleon), $\sigma\sim6.5$ mb.

We would like to examine the differential scattering from this mechanism and the Coulomb potential, at a low energy, say for about 30-Mev K^+ incident on protons. For this purpose we write, in Born approximation,

$$T(\omega,\Delta)\cong t'(\omega,\Delta)+t_c(\omega,\Delta). \tag{8}$$

The quantity Δ is the momentum transfer $=2k\sin(\theta/2)$; $t_c(\omega,\Delta)$ is the Coulomb transition matrix given by

$$t_c(\omega,\Delta)=2\pi e^2/[4k^2\sin^2(\theta/2)], \tag{9}$$

where e^2 is the fine structure constant. The quantity $t'(\omega,\Delta)$ is the following approximate form for the nuclear transition matrix in the Born approximation:

$$t'(\omega,\Delta)=(2\pi)^{-2}(4\omega)^{-1}3(f^2/\mu^2)\lambda(A+B), \tag{10}$$

where

$$A=-\int d\nu\,\frac{p^2}{\nu\Delta}\left\{\tfrac{1}{3}\ln\left|\frac{(a-2b)(a+\frac{1}{2}b)}{(a-\frac{1}{2}b)(a+2b)}\right|+\tfrac{1}{2}\ln\left|\frac{c-2b}{c+2b}\right|+\ln\left|\frac{(d-b)(d+\frac{1}{2}b)}{(d-\frac{1}{2}b)(d+b)}\right|\right\},$$

$$B=\int d\nu\,p^2\nu\Delta\left\{-\left(\frac{1}{4\nu^4a}\right)\ln\left|\frac{a+a'-\frac{5}{2}b}{a+a'+\frac{5}{2}b}\right|+\frac{5}{12\nu^4a}\ln\left|\frac{(a-2b)(a+\frac{1}{2}b)}{(a-\frac{1}{2}b)(a+2b)}\right|+\frac{1}{\nu^4b}\right.$$
$$\left.+\frac{c}{4\nu^4b^2}\ln\left|\frac{c-2b}{c+2b}\right|+\frac{1}{4\nu^4d}+\ln\left|\frac{d+d'+\frac{3}{2}b}{d+d'-\frac{3}{2}b}\right|+\frac{3}{4\nu^4d}\ln\left|\frac{(d-b)(d+\frac{1}{2}b)}{(d-\frac{1}{2}b)(d+b)}\right|\right\},$$

with

$$a=1+(5\Delta^2/4\nu^2),\quad a'=p^2\Delta^2/\nu^4,$$
$$b=p\Delta/\nu^2,$$
$$c=1+(\Delta^2/\nu^2),$$
$$d=1+(3\Delta^2/\nu^2),\quad d'=p^2\Delta^2/2\nu^4.$$

These expressions constitute a good approximation as long as $\Delta_{\max}/\bar{\nu}<1$, since they are obtained in an expansion in powers of this parameter, retaining powers up to the second. Here $\bar{\nu}\sim3\mu$; at 30 Mev, $\Delta_{\max}\sim1.5\mu$ and $\Delta_{\max}/\bar{\nu}\sim0.5$. We take $\lambda/(4\pi)^{\frac{1}{2}}\sim1$.

In Fig. 2 we show the differential cross section from the nuclear scattering and that from the combined nuclear and Coulomb scattering. The total cross section for K^+-proton scattering at 30 Mev is found from Fig. 2 to be about 5.4 mb while the experimental number is probably between 3 and 9 mb.[4]

We turn to a preliminary discussion of the scattering at higher energies. We seek a simple additional contribution to the T matrix at zero momentum transfer [as given by Eq. (4)] which will increase the scattering in the state of isotopic spin one and decrease the scattering in the state of isotopic spin zero. A possible simple additional type of scattering process capable of achieving this result is shown in Fig. 3. This is the "direct" scattering of pseudoscalar K mesons in the S wave. Evaluating this diagram in the Born approximation with neglect of recoil effects and adding this to the t matrix of Eq. (2), we obtain for the modified T matrix[10]

$$\langle\omega|T_\rho|\omega\rangle=\frac{\lambda\alpha/\omega+2\pi Z_\rho/(m+\bar{m}-\omega)}{(1-D-D')+(ik\alpha/2\pi)+[ikZ_\rho/(m+\bar{m}-\omega)]}.\qquad(11)$$

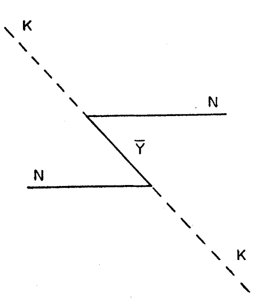

FIG. 3. Feynman graph for the "direct" scattering of a pseudoscalar K meson in the S wave via the intermediate pair state.

In this expression, α and D have been defined previously, D' is given by

$$D'=-Z_\rho\frac{P}{\pi}\int\frac{k'd\omega'}{(m+\bar{m}-\omega')(\omega'-\omega)},\qquad(12)$$

m and $\bar{m}$ are the nucleon and the average Λ-Σ masses, respectively, and the index $\rho=0,1$ refers to the isotopic singlet and triplet states, respectively. The quantities Z_ρ are given by

$$4\pi Z_0=-g_{K\Lambda N}^2+3g_{K\Sigma N}^2,$$
$$4\pi Z_1=g_{K\Lambda N}^2+g_{K\Sigma N}^2,\qquad(13)$$

where the g's characterize the pseudoscalar couplings of pseudoscalar K mesons to Λ particles and nucleons and to Σ particles and nucleons. With the choice of $g_{K\Lambda N}$ and $g_{K\Sigma N}$ given in the introduction,[11] we have $Z_0=-2.8$ and $Z_1=4.4$. This corresponds to an effective attractive potential in the isotopic singlet state and an effective repulsive potential in the isotopic triplet state from the "direct" scattering mechanism. The three K^+-nucleon cross sections, at about 160 Mev laboratory kinetic energy, are then as given in the introduction, in fair agreement with the experimental values[2] in the vicinity of this energy, as deduced from emulsion studies.

CONCLUDING REMARKS

In Eq. (11), with a choice of two coupling parameters, we represent two complex amplitudes which determine

[11] It is interesting to remark upon the difference between $g_{N\Lambda K}^2$ and $g_{N\Sigma K}^2$ ($g_{N\Lambda K}^2/4\pi\sim4$ while $g_{N\Sigma K}^2/4\pi\sim0.4$). In a previous note [S. Barshay, Phys. Rev. **107**, 1454 (1957)], the author remarked upon the possible incompatibility of the equality $g_{N\Lambda K}^2=g_{N\Sigma K}^2$ along with a universal pion-baryon coupling, and the hypothesis of charge independence, in the light of the experimental results on associated production in pion-nucleon collisions. The suggestion was based upon a perturbation estimate. A recent work on symmetries of the strong interactions, by A. Pais [Phys. Rev. **110**, 574 (1958)] has come to my attention, in which similar conclusions are reached by other than perturbation arguments. In the present work, our interactions are charge-independent and we arrive at a marked inequality between the two coupling constants in question. If one considers the lowest order "open" Feynman diagram for the processes $K^-+p\to\Lambda^0+\pi^0$ and $K^-+p\to\Sigma^0+\pi^0$, one readily sees that $g_{N\Lambda K}^2>g_{N\Sigma K}^2$ implies a suppression of Λ^0 production in K^- capture in hydrogen. This has indeed been a striking and puzzling feature of the experimental situation [see L. Alvarez *et al.*, University of California Radiation Laboratory Report 3775, 1957 (unpublished)].

reasonably well the three K^+-nucleon cross sections at about 100 Mev available kinetic energy in the center-of-mass system. This form is simple but is certainly not unique and is meant to give an idea of the strength of the couplings that are likely to be involved in the "direct" scattering. We have no coherent answer to the problem of how the "direct" scattering might be damped at low energies, leaving only the scattering from the exchange of pions. This problem may be similar to the long-standing problem of the apparent smallness of pair effects in the S-wave scattering of low-energy pions by nucleons. A strong attack on the problem must likely await a definitive determination of the K-meson parity, a quantity which enters in so important a manner in the "direct" scattering mechanisms. A remark might be made on the application of Eq. (11) to the K^+-nucleon scattering at the even higher energies now under investigation in emulsion work. At about 150 Mev available kinetic energy in the center-of-mass system, Eq. (11) gives about a 15% increase in the "average" cross section, $\bar{\sigma}=\frac{1}{2}\{\sigma(K^+p)+\sigma(K^+n)\}$ and the charge-exchange to non-charge-exchange ratio is about 0.3. Of course, we are pressing too close to our cutoff (about 200 Mev available kinetic energy) for the numbers to be taken seriously. Preliminary experimental results[12] seems to indicate that the average K^+-nucleon cross section in emulsion may rise from about 12 mb to about 18 mb in the energy interval from, say, 180 to 300 Mev and then level off again. This might be partially due to pion production by K^+ mesons near threshold, although the frequency of this process may be very hard to estimate in emulsion owing to reabsorption of the emerging pions in the nucleus. In this respect, it might be well to remember that the first evidence for appreciable pion production by π^- mesons incident upon nuclear emulsions at moderate energies ($\lesssim$500 Mev) came after a large correction for pion reabsorption was applied to the data.[13] This cast some doubt on the actual frequency of this process.[14] However, the recent Russian experiments[15] on π^--p collisions from 300 to 370 Mev have shown quite clearly the several millibarns of pion production which have been predicted by some recent theoretical calculations.[16,17] Of course, P-wave scattering of the K meson is also likely to be appreciably present at these energies.

In conclusion we summarize the results of the first part of this calculation. The hypothesized four-boson interaction between K mesons and pions, within the framework of this crude calculation, seems capable of simply giving rise to the following experimentally observed features of the low-energy scattering of K^+ mesons by nucleons: (*a*) The scattering is predominantly in the S wave and the cross sections shows a slight rise with increasing energy. (*b*) The effective nuclear potential is respulsive and of relatively short range ($\sim 1/2\mu$). (*c*) The charge-exchange scattering is very small at very low energies. A boson-boson coupling $\lambda^2/4\pi \sim 1$ to 5 seems capable of giving the magnitude of the low-energy K^+ proton cross section.

ACKNOWLEDGMENTS

It is a pleasure to thank Dr. Gustave Zorn for a most helpful discussion on the experimental situation. I would also like to thank Dr. G. Feinberg for several helpful conversations.

[12] Gustave Zorn (private communication).

[13] M. Blau and M. Caulton, Phys. Rev. **96**, 150 (1954).

[14] See, for example, H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, 1955), Vol. II, p. 362.

[15] U. G. Zinov and S. M. Korentchenko, "Pion Production in π^--p Collision Near Threshold," (preprint from the Joint Institute for Nuclear Research, U.S.S.R.).

[16] Saul Barshay, Phys. Rev. **103**, 1102 (1956).

[17] Jerrold Franklin, Phys. Rev. **105**, 1101 (1957).