K^+ Scattering in the Energy Range 100–250 Mev*

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Approximately 65 meters of K^+-meson track was scanned in the energy interval 100–250 Mev. Analysis of the data shows that the K^+-neutron charge exchange scattering rises appreciably above the value $\frac{1}{5}$ corresponding to a pure $I=1$ interaction and at energies $\gtrsim 150$ Mev appears to be larger than the K^+-neutron direct scattering. Analysis of the angular distribution of the inelastic events for K^+ incident energies greater than 150 Mev indicates a nonisotropic center-of-mass angular distribution, peaked towards $\theta_{\text{c.m.}}=180°$.

I. INTRODUCTION

THE experimental elucidation of the interaction of K^+ mesons with nucleons is clearly of interest in order to obtain a basis with which theoretical predictions may be compared. Presumably the program outlined by the π-meson school will be followed and a detailed elucidation of the scattering phase shifts, their variation with energy and isotopic spin dependence will emerge. It appears that as yet we are not in a position to do this with any precision. On the other hand, there does appear to be some fairly striking statements one can make about the scattering. These refer principally to the approximate independence with energy of the K^+-proton scattering cross section[1,2] and the energy variation of the K^+-neutron charge exchange and elastic scattering cross sections.[3] It is with the latter aspect that this paper is concerned.

Qualitatively speaking we have the observation that the inelastic scattering cross section of K^+ with emulsion nuclei (corrected) increases slowly with energy from about 60 to 250 Mev.[3,4] Coupled with the constancy of the K^+-P scattering and an observed increase of inelastic interactions with nuclei in which no K^+ emerges (K^+-neutron charge exchange) we have inferred an approximately constant K^+-neutron cross section but with the charge exchange to noncharge exchange ratio varying appreciably with energy.

II. EXPERIMENTAL

A stack of 80 4 in.×10 in.×400 μ Ilford G-5 emulsions was exposed to a "separated" K^+-meson beam of the Berkeley bevatron.[5] The momentum of the entering beam was centered at 570 Mev/c corresponding to a range in emulsion of 22 cm; the stack dimensions were such that a noninteracting K^+ would come to rest in the emulsion. The method of "on track" scanning was used and the tracks were picked up 1 cm from the leading edge; the K^+ mesons at this point had an ionization corresponding to 1.2 times minimum.

Ending K^+ mesons were identified by their characteristic decays; if the decay products were not visible (because of a slight underdevelopment of the stack) a 10% grain count *vs* range measurement served to distinguish them from protons. Tracks due to particles that interacted in flight, decayed in flight, or left the stack (via the narrow dimensions) were identified by their ionization and the multiple Coulomb scattering. Secondaries from interactions that came to rest in the emulsion stack were identified by their decay modes when visible and in lieu of this, by grain count *versus* range measurements. For secondaries that left the stack, the change in ionization with range was used for discrimination if the tracks were not too steeply dipping; some were too steeply dipping to allow reliable measurements to be made—these are discussed later.

The range histogram of the ending (noninteracting) K^+ mesons showed that most of the tracks had ranges between 20 and 24 cm with an average of 22 cm. The energy of a K^+ at the point of interaction was determined from its expected range at this position; the observed range distribution thus yields an uncertainty of ± 2 cm in expected range. This is reflected in a 5% error in energy at 250 Mev and a 25% error at 100 Mev; the significance of the latter is somewhat diminished since we divided our data into three energy intervals of 50 Mev each from 100 to 250 Mev.

TABLE I. Tabulation of the number and types of inelastic scatterings of K^+ mesons in emulsion in the energy interval 100–250 Mev.

Energy interval (Mev)	Total number of inelastic events	Noncharge exchange events[a] (S)	Charge exchange events[a] (X)	Unclassifiable events	(Charge exchange)[b] / (Noncharge exchange)
200–250	41	21 (25)	14 (16)	6	0.64±0.2
150–200	28	17 (19)	8 (9)	3	0.47±0.17
100–150	21	15 (17)	4 (4)	2	0.27±0.17

[a] The numbers in parentheses represent the corrected number of events obtained by apportioning the unclassifiable events.
[b] The "corrected" number of events was used here.

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[1] H. C. Burrowes *et al.*, Phys. Rev. Letters **2**, 117 (1959).
[2] T. F. Kycia *et al.*, Bull. Am. Phys. Soc. 4, 25 (1959).
[3] M. F. Kaplon, *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958).
[4] J. Lanutti *et al.*, Phys. Rev. **109**, 2121 (1958).
[5] W. H. Barkas *et al.*, University of California Radiation Laboratory Report UCRL-3627, 1956 (unpublished).

TABLE II. Tabulation of corrections applied to obtain K^+-nucleon cross sections from observed K^+-nuclear interactions.

Energy interval (Mev) 1	Track length scanned (meters) 2	Total nuclear cross section uncorrected (mb) 3	σ_n Uncorrected total nucleon cross section (mb) 4	σ_n Corrected for Coulomb repulsion (mb) 5	σ_n Corrected for shading (mb) 6	σ_n[a] Corrected for Pauli principle and potential well (mb) 7	σ_{NX}[a] Neutron charge exchange (corrections 4, 5, 6, 7 applied) (mb) 8	σ_N[b] Total neutron scattering cross section (mb) 9	σ_{NX} (mb) 10	σ_{NS} (mb) 11
200–250	27.5 (41 events)	319±50	7.5±1.2	7.90	11.15	12.5±2	9.5±2.4	10.2±2.5	9.8±4	0 ±4.3
150–200	22.3 (28 events)	269±50	6.3±1.2	6.7	9.4	10.9±2	6.8±2.3	7 ±2.5	7.5±4	1.9±4.3
100–150	14.8 (21 events)	303±65	7.1±1.5	7.65	11.1	14.2±3	5.2±2.2	13.5±3.6	5.2±4	2.3±4.4
100–250	64.6 (90 events)	297±31	6.9±0.7	7.3	10.45	12.1±1.2	7.6±1.4	9.4±1.9	7.7±2.2	1.7±2.5

[a] The Pauli correction as applied here assumes an isotropic center-of-mass angular distribution. Any deviation from this in the direction of favoring forward directions would tend to increase σ_n.
[b] Obtained from $\sigma_n=[Z\sigma_P+(A-Z)\sigma_N]/A$ assuming $\sigma_P=15$ mb. Reference a above is relevant here and could result in an increased σ_N.

The interactions were classified as inelastic if (i) recoil (s) or other tracks in addition to a K^+ emerged from the interaction, (ii) a K^+ did not emerge from the interaction, (iii) if the total range of the K^+ (i.e., range before interaction + range after interaction) was less than 20 cm, and (iv) for tracks identified as K^+ from an interaction but leaving the stack—if there was a detectable change in ionization. The use of criterion (iii) results in a sliding discrimination from elastic events corresponding to 25% at 100 Mev and decreasing to 5% at 250 Mev; (iv) was limited to energy losses $\geq 20\%$.

We shall refer to the inelastic scatterings as charge exchange (X) if a K^+ did not emerge [criterion (ii)] and otherwise as scattering (noncharge exchange) events which we denote by (S). Events with nonidentifiable secondaries were not susceptible to direct classification. The number of events according to energy interval and classification (X) or (S) as well as unclassifiable events and the ratio of charge exchange to noncharge events (corrected) is listed in Table I.

III. REDUCTION OF DATA

The total of 90 inelastic events in the energy interval 100 to 250 Mev were observed in 64.6 meters of K^+-meson track. These interactions are presumably due to the following three basic reactions:

(a) $K^++P\rightarrow K^++P$ denoted by σ_P,

(b) $K^++N\rightarrow K^++N$ denoted by σ_{NS};

$$\sigma_N=\sigma_{NS}+\sigma_{NX},$$

(c) $K^++N\rightarrow K^0+P$ denoted by σ_{NX}.

(a) can occur both with free hydrogen atoms of the emulsion and bound protons of emulsion nuclei while (b) and (c) can occur only with bound neutrons.

The total interaction cross section (uncorrected) for nuclei other than hydrogen is shown for the three energy intervals as well as the total interval in Column 3 of Table II. This cross section divided by the average nucleon number for emulsion nuclei (taken as 43) gives the uncorrected average nucleon cross section of Column 4. The observed nuclear cross section must however be corrected for several effects.[4] It is decreased due to the Coulomb repulsion between the nucleus and the K^+. The correction used[6] for this is

$$\sigma_{\text{obs}}=\sigma[1-Ze^2/(R+\lambda\!\!\!^{-})T],$$

where σ_{obs} is the observed cross section, σ the corrected one, Z the average atomic number, R the nuclear radius, $\lambda\!\!\!^{-}$ the De Broglie wavelength of the K^+ with kinetic energy T. The resultant σ is listed in Column 5.

Another correction must be applied to take into account the fact that the nucleons shade one another; this is made using the curve of Rossi[7] and the result given in Column 6. The Pauli principle inhibits low-energy transfers to bound nucleons; the correction factor given by Sternheimer[8] for K^+ mesons and whose angular distribution is isotropic in the center-of-mass system is

$$\eta=1-0.78(T_F/T_1),$$

where $T_F=25$ Mev is the Fermi energy and T_1 the energy of the K^+ in the repulsive nuclear plus Coulomb well, $V_N+V_C=29$ Mev.[9] The resultant nucleon cross section, σ_n, is given in Column 7. It should be stressed that this correction is sensitive to the assumption of an isotropic center-of-mass K^+-nucleon angular distribution since the effect of the Pauli principle is most

[6] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952), p. 350.
[7] B. Rossi, *High-Energy Particles* (Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1952), p. 363.
[8] R. M. Sternheimer, Phys. Rev. **106**, 1027 (1957).
[9] G. Igo *et al.*, Phys. Rev. **109**, 2133 (1958); they give $V_N=27$ Mev; $\langle V_C\rangle=2$ Mev for $Z=21$.

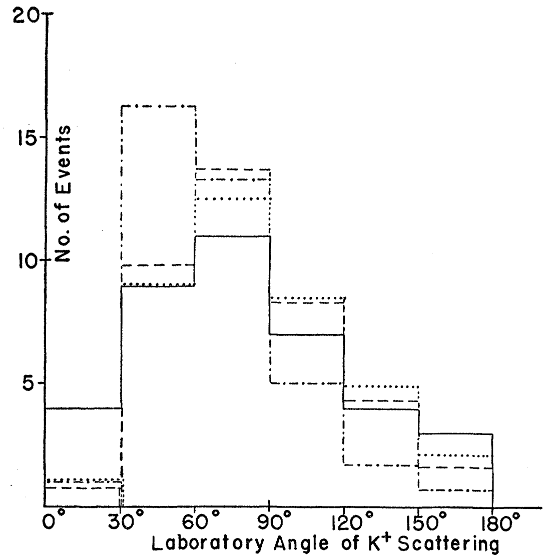

FIG. 1. Observed and derived laboratory angular distributions for K^+-nuclei inelastic scatterings in the range 150–250 Mev. Solid histogram is the observation; the dot-dash, dashed, and dotted histograms result from the assumption of different c.m. angular distributions and have folded in the Fermi motion and Pauli principle. They correspond to (i) isotropy (dot-dash); (ii) $\sigma_{\mathrm{c.m.}}\sim 1.25-1.44\cos\theta+1.93\cos^2\theta$ (dashed); and (iii) $\sigma_{\mathrm{c.m.}}\sim 1-1.5\cos\theta+3\cos^2\theta$ (dotted).

pronounced on forward scatterings. In Column 8 we give the corrected neutron-charge exchange cross section following the procedures above and using the data of Table I.

The corrected nucleon cross section, σ_n, is the weighted average of the proton and neutron cross sections. Ideally it is obtained from

$$\sigma_n=\frac{Z\eta_P\sigma_P+(A-Z)\eta_N\sigma_N}{A},$$

where η_P and η_N are the Pauli correction factors for the neutron and proton separately. Since σ_P is known to be essentially constant with energy ($\sim$15 mb) over this interval and its angular distribution isotropic,[1–3] σ_N can be inferred if we know σ_n. The zeroth-order approximation to this is to assume $\eta_N=\eta_P$; we have done this, with $\sigma_P=15$ mb to obtain the values of σ_N listed in Column 9. Since the evidence (to be discussed later) indicates an appreciable P-wave contribution in the c.m. angular distribution, these values should probably be viewed as lower limits to σ_N (a similar comment may also be applicable to the σ_{NX} of Column 8).

The charge exchange cross section, σ_{NX}, may be obtained in a somewhat different matter which is not as sensitive to the unclassified events. We can write

$$\frac{X}{S}=\frac{\sigma_{NX}}{\sigma_P+\sigma_{NS}}=\frac{\sigma_{NX}}{\sigma_P+\sigma_N-\sigma_{NX}},$$

and take advantage of the apparent constancy of σ_N over our total energy interval to obtain σ_{NX} and thus σ_{NS}. Using the value of $\sigma_N=9.4$ mb, we obtain the values of σ_{NX} and σ_{NS} listed in Columns 10 and 11, respectively.

In order to obtain some idea as to the center of mass (c.m.) angular distribution of the K^+-nucleon scattering we attempted a Monte Carlo calculation[10] using the 38 events in the energy interval 150–250 Mev for comparison. An angular distribution in the c.m. system was transformed to the laboratory system folding in the Fermi motion of the nucleons and the Pauli exclusion principle in order to obtain a laboratory angular distribution. First an isotropic c.m. distribution was assumed; the resultant laboratory distribution is shown in Fig. 1 as the dot-dash histogram—the observed distribution is the solid histogram. Clearly this is not a very good fit. Next the observed laboratory distribution was transformed to the c.m. assuming the target nucleons at rest. This yielded the histogram of Fig. 2; the solid curve is a least squares fit and is of the form $\sigma_{\mathrm{c.m.}}(\theta)\sim 1.25-1.44\cos\theta+1.93\cos^2\theta$. The result of transforming this back to the laboratory is shown in Fig. 1 as the dashed histogram. A second attempt at a better fit to the laboratory distribution was made using a distribution $\sigma_{\mathrm{c.m.}}(\theta)\sim 1-1.5\cos\theta+3\cos^2\theta$; this is shown as the dotted histogram in Fig. 1. It seems clear that an appreciable P-wave contribution exists in the c.m. and that our Pauli principle corrections used in Table II represent only an approximation.

IV. DISCUSSION AND CONCLUSIONS

It seems clear that the accuracy of the data is such as to warrant only a qualitative discussion of K^+-nucleon scattering. The fact that the K^+-P scattering appears to be isotropic, coupled with the observation that our data is not consistent with an isotropic K^+-nucleon scattering leads to the conclusion that the K^+-neutron scattering involves P waves. In the framework of charge independence, the K^+P scattering involves a pure $I=1$ state and the above observation

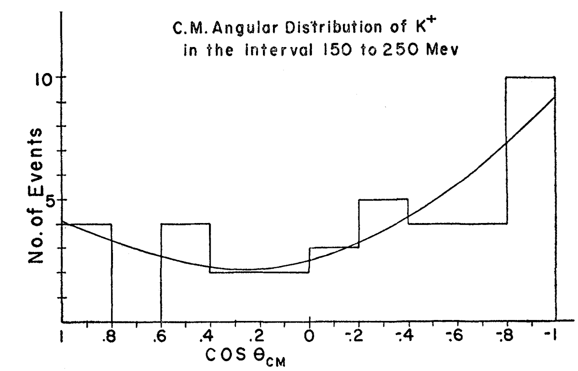

FIG. 2. Derived c.m. distribution of K^+-nucleon scattering obtained from observed distribution of Fig. 1 assuming the target nucleons at rest. The curve is a least squares fit, $\sigma_{\mathrm{c.m.}}\sim 1.25-1.44\cos\theta+1.93\cos^2\theta$.

[10] B. Bhowmik *et al.*, Nuovo cimento **6**, 440 (1957).

then implies that the P-wave amplitude for $I=1$ is quite small.

The K^+-neutron scattering proceeds through both $I=1$ and $I=0$ states; if only the $I=1$ state were involved $\sigma_{NX}/(\sigma_{NS}+\sigma_P)=X/S=\frac{1}{5}$. It is clear from Table I that while this may be satisfied at lower energies, it is certainly not at higher. Thus both the observation of $X/S>\frac{1}{5}$ and a nonisotropic c.m. distribution yield the existence of $I=0$ state with a finite P-wave amplitude. In addition the data indicate that σ_{NX} becomes greater than σ_{NS} with increasing energy, the transition occurring probably somewhat above 150 Mev. This seems to imply that the S-wave $T=1$ and $T=0$ amplitudes interfere destructively at higher energies for if the amplitudes are denoted by $\alpha_L(T)$ we have[3]

$$\sigma_{NS}=\pi\lambda\!\!\!^{-2}\{[\alpha_0(1)+\alpha_0(0)]^2+3\alpha_1^2(0)\},$$

$$\sigma_{NX}=\pi\lambda\!\!\!^{-2}\{[\alpha_0(1)-\alpha_0(0)]^2+3\alpha_1^2(0)\}.$$

This conclusion seems however somewhat difficult to reconcile quantitatively with the angular distribution for the coefficient of $\cos\theta$ in $\sigma_{NS}(\theta)$ is $6\pi\lambda\!\!\!^{-2}[\alpha_0(1)+\alpha_0(0)]\alpha_1(0)$. It seems clear that more direct observation of K^+-nucleon scattering, free of the uncertainties arising from the large corrections involved here are called for.

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