Production Cross Sections of K^+ Mesons by 3-Bev Protons on H, Li, and Cu*

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Liquid hydrogen, lithium, and copper targets were exposed to the Cosmotron 3-Bev external proton beam. Nuclear emulsion stacks were used to detect momentum-analyzed K^+ and π^+ mesons of momentum 280 Mev/c leaving the target at 0° in the laboratory system. Correcting for decay in flight, the π^+/K^+ ratios are (630±110), (290±48), and (304±50) for the respective hydrogen, lithium, and copper targets. The laboratory system differential cross sections for K^+ production are $(4.8\pm1.0)\times10^{-32}$, $(3.5\pm0.7)\times10^{-31}$, and $(3.0\pm0.6)\times10^{-30}$ cm²/sterad Mev per hydrogen, lithium, and copper nucleus respectively. Assuming a K^+ energy dependence proportional to the final state density (energy independent matrix element) the integrated K^+ production cross sections are 0.21, 1.7, and 14.7 mb for hydrogen, lithium, and copper. For a matrix element proportional to the K^+ momentum in the center of mass and assuming a $\cos^2\theta$ distribution the p-p cross section also happens to be 0.21 mb. The π/K ratios indicate that K^+ production by p-p is not suppressed significantly relative to that by p-nucleus and that the Li to Cu Z-dependence of K^+ production appears the same as for π^+ production. Our integrated cross sections suggest that strange particle production by 3-Bev protons occurs ~1% of the time.

I. INTRODUCTION

Nucleon-Nucleon Production

ONE of the elementary strong interactions involving strange particles is the nucleon-nucleon production of a strange particle pair:

$$N+N\rightarrow(\Lambda \text{ or } \Sigma)+K+N.$$

At present little is known about this process experimentally. In fact no experimental cross sections have been determined for strange particle production by protons on hydrogen. Only order of magnitude estimates have been given so far.[1–6] In the hydrogen diffusion cloud chamber experiments a grand total of 4 pictures of strange-particle production by p-p have been seen.[1–3] These results are consistent with a production cross section ~1% of geometrical for 3-Bev protons. Lindenbaum and Yuan, using liquid hydrogen target and counter techniques, have a preliminary result of 12 counts interpreted as K-mesons which is also consistent with ~1% of geometrical.[6] On the other hand, there are one diffusion cloud chamber experiment[4] and one counter experiment[5] which agree best with a production cross section smaller by an order of magnitude.

The experiment reported here used a liquid hydrogen target in the full external 3-Bev proton beam of the Cosmotron. Positive particles of 280 Mev/c leaving the target at 0° in the lab (laboratory) system were magnetically analyzed and detected in nuclear emulsion stacks. Figure 1 shows the geometry used. A lab differential cross section of $(4.8\pm1.0)\times10^{-32}$ cm²/sterad Mev for K^+ production was obtained. The total cross section for K^+ can be estimated by integrating over the K^+ phase space with the result ~0.2 mb which is ½% of geometrical.

Nucleon-Nucleus Production

We have also measured differential K^+ production cross sections from lithium and copper targets and find cross sections also of the order of 1% of geometrical. Our results are given in Table I. The first indications of such a high K^+ yield from protons on copper were from the momentum analyzed K^+ beams of the Bevatron and Cosmotron.[7,8] Assuming each Cosmotron internal proton traversed the entire target length once,

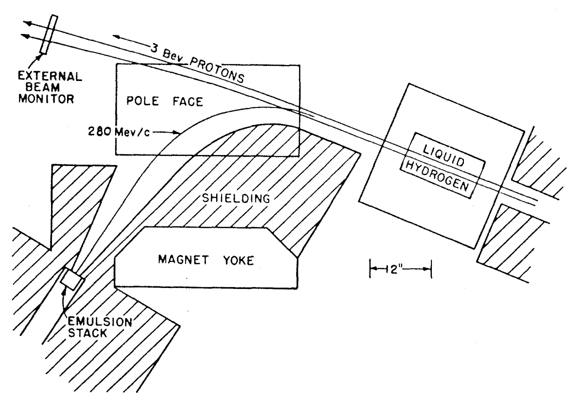

FIG. 1. Experimental setup in the Cosmotron external beam showing positions of liquid hydrogen target, analyzing magnet, and nuclear emulsions.

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[1] Block, Harth, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **99**, 261 (1955).
[2] Wright, Powell, Maenchen, and Fowler, Bull. Am. Phys. Soc. Ser. II, **1**, 386 (1956), and private communication.
[3] Fowler, Kraybill, and Lea, Bull. Am. Phys. Soc. Ser. II, **2**, 222 (1957).
[4] Cool, Morris, Rau, Thorndike, and Whittemore, Phys. Rev. **108**, 1046 (1957).
[5] D. Berley and G. B. Collins, Bull. Am. Phys. Soc. Ser. II, **1**, 320 (1956).
[6] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **105**, 1931 (1957).
[7] Kerth, Stork, Birge, Haddock, and Whitehead, Phys. Rev. **99**, 641 (1955).
[8] Harris, Orear, and Taylor, Phys. Rev. **101**, 1214 (1956).

TABLE I. 3-Bev p-p, p-Li, and p-Cu results. The differential cross sections are in the laboratory system for particles of 280 Mev/c momentum at 0°. The total cross sections for K^+ production, $\sigma_K{}^a$ and $\sigma_K{}^b$, are obtained from the differential cross sections by making certain assumptions about the K-meson energy and angle distributions.

	π^+/K^+	$d^2\sigma_K/d\omega dT$ cm²/sterad Mev	$d^2\sigma_\pi/d\omega dT$ cm²/sterad Mev	$\sigma_K{}^a$ mb	$\sigma_K{}^b$ mb	$\sigma_K{}^a/\sigma_{total}$
H	630±110	$(4.8\pm1.0)\times10^{-32}$	$(1.65\pm0.28)\times10^{-29}$	0.21	0.21	0.005
Li	290±48	$(3.5\pm0.7)\times10^{-31}$	$(5.6\pm0.1)\times10^{-29}$	1.7	···	0.007
Cu	304±50	$(3.0\pm0.6)\times10^{-30}$	$(5.1\pm0.9)\times10^{-28}$	14.7	···	0.011

[a] Assuming a production matrix element which is constant.
[b] Assuming a matrix element proportional to the K-meson momentum in the c.m. system and a K-meson angular distribution of $\cos^2\theta$ in the c.m. system.

we had estimated from earlier data[8] that the K^+ cross section was order of magnitude a few percent of geometrical. The proton on iron results of Cool *et al.*,[4] are in agreement. The published estimated cross sections of Ridgway, Berley, and Collins are lower.[9] However, more recent information on the Σ^+ lifetime and branching ratios to π^0 decay modes have caused them to increase their original estimates.[10] These comparisons are discussed in more detail in Sec. IV.

From our lithium and copper π/K ratios the Z-dependence for K^+ production appears the same as the Z-dependence for pion production. Our results suggest that direct nucleon-nucleon production is sufficient to explain strange particle production by protons on nuclei. If production by intermediate pions predominated, one would obtain lower cross sections, and the hydrogen cross section relative to the lithium and copper would be much smaller than that observed in this experiment.[11]

II. EXPERIMENTAL DETAILS

Magnet System

The full external Cosmotron 3-Bev proton beam[12] passed through two strong focusing magnets and then was deflected 6° by a bending magnet of 6-inch gap before passing about 20 feet through the shield wall to our target position. The beam was focused to a spot of ~1 inch diameter at the target position. The 3-Bev protons passed through the 18×36 inch analyzing magnet shown in Fig. 1. This magnet of 6-inch gap, deflected particles of momentum 280 Mev/c through 77° and focused them in the horizontal plane at the emulsion stack position. The path length from target center to emulsion was 230 cm. There was a small amount of defocusing in the vertical plane. The effective aperture and dispersion of the analyzing magnet were determined both by calculation and by wire measurements and agree within errors. The dispersion, dT_K/dy (change of energy per cm of lateral displacement at the emulsion), was also checked by measuring the lateral variation of proton range in the emulsion.

Monitoring

The number of protons passing through the target was determined using the external beam analyzer designed and calibrated by Dr. C. Swartz. This was an 8×8×2 inch thick water Čerenkov counter. A NaI crystal screen, which permitted each pulse to be observed by remote TV, was placed at the downstream face of this monitor. At this position the spot size was ~2 inches in diameter. No drift in spot position occurred during any of the exposures. The accuracy of the monitor calibration is ±10%.

Hydrogen Target

At the time this experiment was being planned, the prevailing opinion was that the p-p cross section for strange particles was considerably smaller than that from larger nuclei. For this reason we designed a hydrogen target and experiment which would have a high effective thickness of hydrogen with a window thickness as small as possible. One can use a long target and still obtain good focusing by looking at 0° in the lab. We decided on a Styrofoam target which would hold 15 inches of liquid hydrogen in the beam direction with 6-inch diameter windows of $\frac{1}{2}$-mil Mylar. The heat leak through the windows was minimized by using double windows on the two Styrofoam boxes with dead spaces of hydrogen gas between them. In addition to the two Mylar windows on the inner copper can and the two on the outer aluminum box, there were then 4 windows on each Styrofoam box. The liquid hydrogen loss rate was about 5 liters/hr when filled to ~25 liters. The target was constructed at Brookhaven National Laboratory under the direction of Dr. R. Adair and Mr. W. Schlafke.

The proton beam traveled in helium bags both before and after the target. There was ~0.17 g/cm² of helium, air, and windows in the beam path up to a distance of 1.5 K^+ decay lengths from the emulsion stack position. During the run the windows of the hydrogen target accumulated a layer of frost estimated to be less than ~0.04 g/cm².

Scanning

Emulsion stacks were exposed to targets of liquid hydrogen, lithium, and copper. In addition background stacks were exposed to the empty liquid hydrogen

[9] Ridgway, Berley, and Collins, Phys. Rev. **104**, 513 (1956).
[10] D. Berley and G. B. Collins (private communication).
[11] Fowler, Taft, and Mosburg, Phys. Rev. **106**, 829 (1957); G. T. Reynolds and S. B. Treiman, Bull. Am. Phys. Soc. Ser. II, **2**, 221 (1957); and R. Jastrow, Phys. Rev. **97**, 181 (1955).
[12] Piccioni, Clark, Cool, Friedlander, and Kassner, Rev. Sci. Instr. **26**, 232 (1955).

TABLE II. Exposure conditions and K^+ and π^+ fluxes found in the five stacks which were exposed.

Target	Target thickness (g/cm^2)	Beam protons N_p	Number of K's found	K^+ flux at stack I_K (K/cm^2)	π^+ flux at stack $I\pi$ π/cm^2
H	2.6	2.28×10^{12}	60	84.3	1.72×10^5
Li	12.7	1.64×10^{12}	59	290	2.68×10^5
Cu	11.3	1.20×10^{12}	63	176.4	1.74×10^5
Empty H		1.90×10^{12}	6	5.9	3.05×10^4
No target		0.92×10^{12}	not scanned		1.84×10^4

target and to no target at all. All scanning was along-the-track. The pickup strip was 2 cm from the leading edge (0.9 cm residual range for K^+) and all gray tracks within the proper dip and azimuth limits were followed. Only tracks with visible secondaries were accepted as K-mesons. Tracks with no apparent secondary were grain counted at 1 cm residual range in order to separate protons from the K-mesons. The ends of tracks which had a K-meson grain count were critically examined for secondaries. About 2% of the gray tracks followed were K-mesons. The rest were mainly protons which passed through the K-ending region. We believe most of these background protons were produced in the helium gas inside the magnet gap and thus had no momentum selection in our geometry. The over-all efficiency for finding K-mesons was estimated to be 91% by rescanning and by examining the dip, azimuth, and range distributions of the K-meson tracks.

III. RESULTS

The pertinent data are shown in Table II. The π/K ratio at the target is obtained by using the correction factors 1.10 and 3.08 for decay in flight of the π^+ and K^+, respectively. The corrected π/K ratios are presented in Table I. The absolute differential cross sections are obtained by the relation

$$\frac{d^2\sigma_k}{d\omega dT}=\frac{I_K'}{N_p n_t \theta_H (d\theta_V/dz)(dT/dy)_K},$$

where I_K' is the number of K^+/cm^2 corrected for decay in flight, N_p is the average number of beam protons passing through the target, n_t is the number of target nuclei/cm^2, $\theta_H=0.237\pm0.012$ radian is the horizontal acceptance angle, $d\theta_V/dz=(3.90\pm0.27)\times10^{-3}$ rad/cm is the vertical acceptance angle per cm at the stack, and $(dT/dy)_K=1.53\pm0.08$ Mev/cm is the horizontal dispersion per cm at the stack. The resulting differential cross sections for K^+ and π^+ production are given in Table I. The c.m. (center-of-mass) system p-p cross section for K^+ production is

$$\frac{d^2\sigma_K}{d\bar{\omega}d\bar{T}}=(4.5\pm0.9)\times10^{-32}\text{ cm}^2/\text{sterad Mev},$$

for $\theta=180°$ and kinetic energy $\bar{T}=67$ Mev.

The p-p cross sections have been corrected for background by subtracting the K^+ and π^+ fluxes per monitor count found in the empty target exposure. This K^+ background correction is (8.4 ± 4.2)% and is what would be expected from the 0.2 g/cm^2 of nonhydrogen in the beam. The empty target stack has a pion flux per monitor count which is 21% of the pion flux when the target is filled with hydrogen. The fact that the background correction for pions is larger than that for K's is reasonable, since, having a much larger decay length (50 ft), pions can be produced in the helium upstream from the target and still reach the emulsion stack.

The copper and lithium pion cross sections have been corrected for the pion background found in the no-target exposure. No background correction has been made for the copper and lithium K^+ cross sections since this would be at most a 3% correction as determined by the K flux found in the stack exposed to the empty target.

The total cross sections for K^+ production have been estimated using the relations

$$V_r\frac{d^2\sigma_K}{d\bar{\omega}d\bar{T}}=\frac{2\pi}{\hbar}|M|^2\rho(\bar{T}),$$

$$V_r\sigma_K=\frac{2\pi}{\hbar}\int_{\bar{\omega}0}^{\bar{T}_{\max}}|M|^2\rho(\bar{T})d\bar{T}d\bar{\omega},$$

where M is the production matrix element, V_r is the relative velocity of the 2 protons, and $\rho(\bar{T})$ is the density of final states integrated over all nucleon-hyperon directions for a given K-meson energy $\bar{T}$. All the above quantities are in the c.m. system. We have used the exact relativistic expression for the density of states of three particles of unequal masses as given by Block, Harth, and Sternheimer.[13] We have considered the cases where $|M|^2$ is a constant, and where $|M|^2\propto p^2$ assuming a $\cos^2\theta$ distribution of the K in the c.m. system. Here p is the K^+ momentum in the c.m. system. A K^+ meson must be produced in association with either a Λ or a Σ hyperon according to the following modes.

$$p+p\rightarrow\begin{cases}p+\Lambda^0+K^+\\ p+\Sigma^0+K^+\\ n+\Sigma^++K^+.\end{cases}$$

The production modes with associated K^- or pions are neglected here because of the nearness to their thresholds. If the K^+ production is in association with Λ's only, the integrated cross sections are 0.25 mb and 0.28 mb for the constant and $p^2\cos^2\theta$ matrix elements, respectively. If the K^+ production is with Σ's only, the corresponding cross sections are 0.19 mb and 0.18 mb. Our experiment was at such a momentum that the above 4 estimates happen to be fairly close to each other. However, we would expect the uncertainty of this type of estimate to be at least a factor two. The K^+ cross sections given in Table I and the plots of

[13] Block, Harth, and Sternheimer, Phys. Rev. **100**, 324 (1955).

differential cross section *vs* energy in Fig. 2 were obtained by assuming equal matrix elements for the above three production modes.

The integrated K^+ cross sections for copper and lithium which are shown in Table I have been estimated by using the curves of Block, Harth, and Sternheimer.[13] They average the proton-nucleon phase space over a Gaussian nucleon Fermi momentum distribution.

IV. DISCUSSION

Z-Dependence

Our production cross sections are dependent upon the monitoring system and the magnet geometry determinations. The π/K ratios for the different targets are not dependent on these determinations and therefore should be a more direct indication of the Z-dependence of the strange particle production cross section. The lithium and copper π/K ratios are about the same, which suggests that, within the errors quoted, the K^+ Z-dependence is the same as the π^+ Z-dependence. From our lithium and copper differential cross sections it appears that the π^+ Z-dependence is linear with atomic weight within the errors.

Our π/K ratio from hydrogen is about a factor two higher than that from copper or lithium. Lindenbaum and Yuan[6] observed the same effect at 60° in the lab system. We do not feel that one is justified in concluding that the p-Cu interaction is twice as effective as the p-p for producing K^+, or that the p-n cross section for K^+ should be larger than the p-p. This is because of several complicating factors which are difficult to evaluate. One of these factors is that the nucleon-nucleon cross section for strange particles may be increasing quite rapidly with energy at 3 Bev,[14] so that

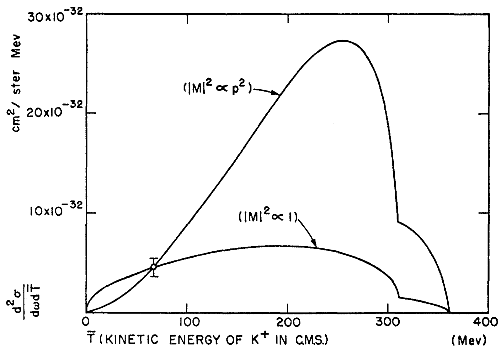

FIG. 2. 3-Bev p-p differential cross section for K^+ production in center-of-mass system as a function of the K^+ kinetic energy. These two curves are fitted to our experimental point for K^+ of 67 Mev at 180° in the c.m. system. The two shapes are determined by the two assumptions: $|M|^2 \propto 1$ and $|M|^2 \propto p^2$ where p is the c.m. system K^+ momentum. The Λ and Σ processes are combined as discussed in Sec. III. (Note that the $|M|^2 \propto p^2$ curve is reduced by the factor $\cos^2\Theta$ for angles other than 0° or 180°.)

[14] J. Hornbostel and E. Salant (private communication) inform us that they have p-Be data which indicate an increase in K^+ yield as a function of proton energy which is faster than would be expected from phase space alone.

because of Fermi momentum, the average proton-nucleon cross section in the nucleus would be greater than the 3-Bev value. Another factor to be considered is that one expects more π^+ from p-p collisions than from p-n. This would be the case if both p-p and p-n gave the same average number of pions at 3 Bev. The similarity of our K^+ abundances from p-p and p-nucleus is evidence against intermediate pions as the chief mechanism for strange particle production in nuclei. Also, the intermediate pion model predicts K^+ production cross sections much smaller than the values given in Table I.[11]

Our similarity of K^+ abundances from p-p and p-nucleus is in agreement with Lindenbaum and Yuan,[6] but is not in agreement with the conclusions of Cool, *et al.*,[4] and Berley and Collins.[5] Cool *et al.*, conclude that the P-Fe interaction is at least 4 times more effective than the p-p for producing strange particles. Berley and Collins have a p-p effect close to zero with an upper limit which is $\frac{1}{6}$ of the p-d cross section for strange particles which decay into neutral pions.

It should be noted that our differential cross sections per gram for K^+ production from H, Li, and Cu are all the same within the errors.

P-*P* Cross Sections

There are at this time no measurements with which to compare our absolute differential cross sections. However, order of magnitude comparison can be made with the integrated cross sections for K^+ production. The integrated cross section can be obtained from the measured differential cross section by assuming a particular energy and angle dependence for the production matrix element. We calculated the cross section for the following two cases: $|M|^2 = $ a constant, and $|M|^2 \propto p^2 \times \cos^2\theta$. The constant matrix element might be expected for a scalar interaction. The $p^2 \cos^2\theta$ dependence, which is similar to that found in pion production, might be expected for a hyperon and K-meson of opposite parity. In fact, one can learn about the relative parities of the Λ, Σ, and K by observing the K-meson energy and angle distributions near threshold.[15] Our present experiment was in such a momentum region that both of our choices for $|M|^2$ happened to give 0.2 mb for the integrated cross section. Since this experiment does not detect the production mode $p+p\rightarrow p+\Sigma^+ + K^0$, the cross section for all strange particle production should be greater than our value of 0.2 mb for the K^+ modes. According to conservation of isotopic spin, the K^0 mode may be zero, but it cannot exceed three times the other $\Sigma - K^+$ modes.[15] This puts an upper limit of $\sim$0.8 mb for all strange particle production by p-p at 3 Bev.

In comparing our integrated cross sections with those from other experiments, three points should be remembered. The first is that the total data are still meager. Second is the fact that none of the cross sections are

[15] G. Feldman and P. T. Matthews, Phys. Rev. (to be published).

measured directly, but all were calculated by assuming particular K-meson energy and angular distributions. A change in these assumptions will affect the various experimental results quite differently. For instance, the assumption of a K-distribution strongly peaked forward and back would decrease the cross section as calculated in this experiment, but would increase the cross sections of Cool *et al.* and of Berley and Collins. The third point to be remembered is that the different experiments measure different production processes. Our experiment detects K^+, that of Berley and Collins detects Λ^0, Σ^0, Σ^+, and K^0, and that of Cool *et al.* detects short-lived strange particles. However, these two experiments should be quite sensitive to all the K^+ modes detected in this experiment, since the K^+ must be accompanied by either a Λ^0, Σ^0, or Σ^+.

Both Cool *et al.* and Berley and Collins use a constant matrix element to estimate their integrated cross sections. Cool *et al.* get an upper limit of 0.2 mb for strange particle production by p-p which is the same as our estimated value. Using the recently determined branching ratios of $\Lambda^0 \rightarrow n+\pi^0$ and $K^0 \rightarrow 2\pi^0$,[16] Berley and Collins estimate an upper limit of $\sim$0.013 mb for strange particle production by p-p.[10] This is an order of magnitude lower than that expected from our results.

Our value of 0.2 mb is 0.7% of the 28 mb total inelastic p-p cross section at 2.6 Bev.[17] This is just as large as the several π-p cross sections for K^+ which have been measured.[18] Our value agrees with the one associated production in 202 p-p interactions at 2.6 Bev seen by Block *et al.*,[1] and with the two events in 94 p-p interactions at 5.3 Bev seen by Wright *et al.*[3] Because of the nearness to threshold, the one event seen by Fowler *et al.*[2] at 1.95 Bev is also in agreement.

A theoretical estimate of the 3 Bev p-p cross section for strange particle production has been made by Serber using a modified Fermi statistical model approach.[19] He obtained a result of $\sim$0.5 mb which is somewhat higher than our value.

P-Nucleus Cross Sections

Our estimated p-Cu cross section of 14.7 mb is 2% of the total neutron-copper absorption cross section of 670 mb at 1.4 Bev.[20] This is consistent with the 7.4±1.5 mb cross section for strange particle production by 3-Bev protons on iron obtained by Cool *et al.* Ridgway, Berley, and Collins estimate $\sim$1 mb per carbon nucleus for strange particle production.[9,18] This is to be compared to our estimate of 1.7 mb for protons on lithium. We and Berley and Collins expect our integrated cross section estimates to be uncertain by at least a factor two.

Another way of estimating the p-Cu cross section is to use what little knowledge one has of the π^+ production cross section at 3 Bev, and calculate back from the several π/K ratios which have been obtained.[6,8] Such estimates give the result that strange particle production should be $\sim$1% of the total cross section.[21]

In summary, our π/K ratios indicate that K^+ production by p-p is not suppressed significantly relative to that by p-nucleus and that the Z-dependence appears the same as for π^+ production. Our differential cross sections give rise to estimates of an integrated strange particle production cross section by 3-Bev protons $\sim$1% of geometrical.

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[16] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento **5**, 1700 (1957).

[17] Chen, Leavitt, and Shapiro, Phys. Rev. **103**, 211 (1956).

[18] D. Glaser, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957), p. 25.

[19] R. Serber, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957), p. 6.

[20] Coor, Hill, Hornyak, Smith, and Snow, Phys. Rev. **98**, 1369 (1955).

[21] R. Sternheimer (private communication).