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Results which suggest that the pion is capable of carrying directional information have continued to appear with some persistence since 1950.[1-4] These indications have not been accepted at face value because the established concept of the pion admits no such capability, and because there seems to be no discernible connection between the different observations. This lack of consistency leads one to suspect that process history may be relevant if the reported phenomena are real. It therefore seemed worthwhile to look for correlations between the π-μ-e decay chain and observables of processes which included and preceded creation of the pion.

Four classes of events detected in nuclear emulsion have been analyzed. These are:

$$K^- + \text{Nucleus} \to \Sigma^+ + \pi^- + \text{Nucleons}$$
$$\quad \llcorner\ \Sigma^+ \to \pi^+ + n$$
$$\qquad \llcorner\ \pi^+ \to \mu^+ + \nu_\mu$$
$$\qquad\quad \llcorner\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$K^+ \rightarrow \pi^+ + \pi^0$$
$$\quad \llcorner\ \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\qquad \llcorner\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$
$$\quad \llcorner\ \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\qquad \llcorner\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$$
$$\quad \llcorner\ \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\qquad \llcorner\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

The initial directions of the π^+, μ^+, and e^+ were measured for all events. The Σ^+ events included only those for which the associated π^- was followed to rest and were drawn from two different emulsion stacks. The K^+ events were all contained in one stack whose exposure orientation relative to the K^+ beam production and transport is known. All K^+, π^+ and μ^+ decays occurred at rest and the e^+ track was observed in all cases except a very few wherein the μ ending was located near a pellicle surface. Since the μ and e were invariably found by the track following method there should be no scanning bias connected with their emission directions. For all three stacks used the original pellicle thicknesses at standard points had been determined so that shrinkage factors could be accurately measured at any desired time. Each stack had its edges milled after assembly, and a carefully aligned coordinate grid was contact printed on the bottom surfaces of the pellicles.

Σ^+ Events

The K^- beams entered both stacks in directions parallel to the pellicle surfaces. All momentum directions were determined by measuring dip angles with the fine z-motion of a microscope and a calibrated eyepiece reticle, and by measuring projected angles in the focal plane with a goniometer. All measurements were repeated by an independent observer. The sample included 77 events, of which 49 involved Σ^+ decay at rest and 28 Σ^+ decay in flight. Eleven of the events represent K^- interactions with free protons and for 3 of these the Σ^+ decayed in flight.

Since the π^+ and μ^+ decays occurred at rest the initial direction distributions for the muons and electrons are expected to be isotropic in the laboratory frame. The data are in agreement with this expectation--none of the muon and electron direction cosine distributions display any significant deviation from isotropy. A departure from expectation has, however, been observed. The relevant distribution involves a unit vector along the relative coordinate between the π^- and Σ^+ at production. This vector is defined to be

$$\hat{R}_\Sigma = \frac{\beta_\Sigma \hat{\Sigma} - \beta_\pi \hat{\pi}_m}{|\beta_\Sigma \hat{\Sigma} - \beta_\pi \hat{\pi}_m|}$$

where $\hat{\Sigma}$ is a unit vector along the initial direction of the Σ^+, $\hat{\pi}_m$ is a unit vector along the initial direction of the π^-, and the β's have their usual meaning.

Now consider the quantity

$$(\hat{\pi} \cdot \hat{R}_\Sigma)(\hat{\mu} \cdot \hat{R}_\Sigma)$$

where $\hat{\pi}$ is a unit vector along the initial direction of the π^+ and $\hat{\mu}$ is similarly defined for the μ^+. (A typical measurement error for one of the cosines which appears in the above expression is ± 0.05). The distribution of this quantity is expected to contain equal numbers of positive and negative members since the muon initial directions should be isotropically distributed and uncorrelated with anything that has gone before the π-μ decay. This is not so for the sample of events available for this analysis. The experimental distribution of $(\hat{\pi} \cdot \hat{R}_\Sigma)(\hat{\mu} \cdot \hat{R}_\Sigma)$ contains 23 positive and 54 negative members. The probability (from the binomial distribution) of seeing a deviation from expectation no smaller than the experimental one is 2.7×10^{-4}. The eleven collinear events include 2 for which the above product is positive and 9 for which it is negative.

It was mentioned earlier that 28 of the Σ^+ decayed in flight. In view of this and the introduction of a relative production coordinate above, it might seem more appropriate to use the relative direction between neutron and π^+ at the Σ^+ decay rather than simply the laboratory emission direction of the π^+. This leads to essentially the same distribution (25 positive, 52 negative). A preliminary version of the preceding results has been reported earlier.[5]

$K_{\pi 2}$ Events

The 700 MeV/c K^+ were produced at 27.5° by the internal proton beam of the Bevatron and passed successively through a vertical collimator, H type bending magnet (37°), horizontal collimator, electromagnetic separator, quadrupole, third collimator, C type steering magnet (11.5°), slit, and absorber. The beam entered the stack in a direction normal to the pellicle surfaces immediately behind the absorber whose purpose was to reduce the K^+ momentum to an appropriate value. A detailed description of the beam transport system has been given by G. Goldhaber, et al.[6] The stack was located about 3.5 feet from the end of the C type steering magnet and approximately along its center line. This fact allows one to estimate that the stray magnetic field present in the stack at exposure was less than 100 Gauss and aligned along the vertical direction.

The initial directions of the pion, muon, and electron were measured with the same technique used for the Σ^+ events. Again no significant departure from isotropy was observed for the muon and electron direction cosine distributions. The distribution of pion initial directions is not isotropic because these particles (range = 12cm) stopped in the stack only for initial directions contained within restricted cones.

The result obtained for the Σ^+ events suggested that it might be useful to seek unexpected sign asymmetries for functions involving a relative coordinate at the production process for the K^+ events. This suggestion provided the motivation for the definitions

$$\hat{R} = \frac{\hat{K} - \hat{P}}{|K - P|}$$

$$\hat{i} = \frac{\hat{P} \times \hat{K}}{|P \times K|}$$

where $\hat{P}$ is a unit vector along the proton beam direction and $\hat{K}$ is a unit vector along the K^+ momentum at production. The vector $\hat{i}$ is directed along the vertical direction in the laboratory and is also parallel to one of the coordinate axes established in the stack. Since the momenta involved are quite large, the vector $\hat{R}$ should represent to within a reasonable are quite large, the vector $\hat{R}$ should represent to within a reasonable

approximation the direction of the relative coordinate between the center of mass of the other products of the primary interaction and the K^{+}.

A large number of distributions involving all or some of $\hat{R}$, $\hat{i}$, $\hat{\pi}$, $\hat{\mu}$, and $\hat{e}$ were tested for asymmetry. One of these has a readily apparent physical meaning and exhibits a large sign asymmetry. It is convenient to introduce the following notation

$$A = \hat{\pi} \cdot (\hat{R} \times \hat{i})$$

$$B = \hat{\mu} \cdot \frac{\hat{\pi} \times \hat{i}}{|\pi \times i|}$$

$$C = \hat{e} \cdot \frac{\hat{\mu} \times \hat{i}}{|\mu \times i|}$$

The last expression is the dot product of $\hat{e}$ with a unit vector which is normal to both the initial direction of the muon and the direction along which the stray magnetic field is aligned. Therefore the distribution of the quantity C is expected to be uncorrelated with anything that preceded the μ-e decay. The experimental results do not agree with this expectation--the distribution of the product CBA contains 19 positive and 61 negative members. This result is depicted in Fig. 1(a) where the distribution of $C \frac{B}{|B|} \frac{A}{|A|}$ has been plotted so that the expected distribution would be flat. The probability (again from the binomial distribution) of seeing a sign asymmetry no smaller than that exhibited by the data is 1.4×10^{-6}. However, a somewhat more conservative estimate of the deviation from expectation is appropriate because a large number of different distributions were tested for sign asymmetry. The product CBA can be thought of as belonging to a certain class of functions. Let F be the dot product of $\hat{\pi}$ with one of $\hat{R}$, $\hat{i}$ and $(\hat{R} \times \hat{i})$, G be the dot product of $\hat{\mu}$ with one of $\hat{R}$, $\hat{i}$, $\hat{\pi}$ and cross products of pairs of these, and H be the dot product of $\hat{e}$ with one of $\hat{R}$, $\hat{i}$, $\hat{\pi}$, $\hat{\mu}$ and cross products of pairs of these. Then the class of functions FGH contains 180 different members. If one now makes the incorrect but simplifying assumption that the corresponding distributions are mutually independent it follows that the probability for one of these to exhibit a sign asymmetry as large or larger than that observed for CBA is 2.5×10^{-4}.

In order to see the physical meaning of CBA, view the plane normal to $\hat{i}$ from above. The sign of $\hat{\pi} \cdot (\hat{R} \times \hat{i})$ then specifies whether the projection of $\hat{\pi}$ on this plane is to the right (+) or left (-) of $\hat{R}$. Similar statements may be made about B and C. Then, for example, BA is somewhat analogous to measurements commonly made in double scattering experiments. The full product, CBA, is just a generalization of this analogy to three decay vertices. It should be mentioned here that there is no significant sign asymmetry for any of the distributions C, B, A, CB, CA, and BA.

A search for a maximum effect was made by replacing $\hat{i}$ and $\hat{R}$ by two orthogonal but otherwise variable unit vectors. This search showed that the maximum effect is indeed obtained with $\hat{i}$ and $\hat{P}$. A plot of values of the expression

$$\frac{N_+ - N_-}{N_+ + N_-}$$

is shown in Fig. 1(b). Here, A has been replaced in CBA by $\hat{\pi} \cdot \hat{V}$ where $\hat{V}$ is a variable unit vector lying in the plane normal to $\hat{i}$ and the subscripts for the N's refer to the sign of $CB(\hat{\pi} \cdot \hat{V})$. There is not a great deal of difference in the asymmetries for $\hat{V} = \hat{K}$, $\hat{V} = \hat{P}$, and $\hat{V} = (\hat{R} \times \hat{i})$.

The last of these seems preferable however, because CPA then has a pleasing symmetry and the physical meaning outlined before.

τ and τ' Events

The measurement of initial directions was carried out in a different manner for these events. The coordinates of two points on each track were measured and recorded with a digitized microscope which produced punched card output. This technique was evolved for the rapid measurement of π directions for a large sample ($\sim$ 3000) of τ events and enables one to determine the pion energies without following the tracks to their ends. The direction cosine distributions for least energetic, intermediate energy, and most energetic pions were plotted for all available τ decays. These proved to be completely isotropic, in agreement with expectation.

Those τ events having one pion with kinetic energy less than 5 MeV were segregated from the main sample and the low-energy pion track followed. In this manner were obtained 316 events for which all of $\hat{\pi}$, $\hat{\mu}$, and $\hat{e}$ have been measured. The τ' events were found during the same scan as the τ events, and $\hat{\pi}$, $\hat{\mu}$, and $\hat{e}$ have been measured for 372 τ' decays. The pion kinetic energies were all less than 35 MeV for the τ' sample. For neither the τ nor the τ' sample was there any significant departure from isotropic behavior of $\hat{\mu}$ and $\hat{e}$ in the laboratory system.

The distributions of

$$D = C \frac{B}{|B|} \frac{A}{|A|}$$

for τ and τ' were plotted and examined. They depart considerably from the expected flat behavior, and the τ' data look exactly like those for the τ folded about 0. Therefore the sum distribution of D for τ and

-D for τ' is presented in Fig. 2. The corresponding value of chi-squared, calculated on the basis of a flat distribution, is 43.8. The expected value of chi-squared is 15.5 and the probability of obtaining a value greater than or equal to that observed is 1×10^{-3}.

All computer programs used in the calculations have been thoroughly checked and each of the unexpected distributions observed has been computed with at least two independently written programs. The measurements are viewed with confidence because checks exist and because in all cases the distributions of more than one measured direction proved to be isotropic as expected. This last fact also militates against the supposition that distortion effects are to be blamed. Furthermore, it seems exceedingly improbable that distortion effects could lead to these apparent several-stage correlations.

It appears that there are two possible explanations of these results--either they consist of a conjunction of individually improbable statistical fluctuations or they represent real phenomena. The realization of the latter possibility would have profound consequences. The $K^{\pm}$ and $\pi^{\pm}$ are presently believed to be zero spin particles incapable of carrying any directional or topological information. Also, no matter what the source of the muons might have been, the apparent $K^{\pm}$ decay effect cannot be explained on the basis of the accepted concept of the muon. Cvijanovich, Jeannet and Sudarshan[6] have proposed the existence of a spin-one particle degenerate in mass with the pion. This alone, however, would not suffice to explain the $K^{\pm}$-decay results.

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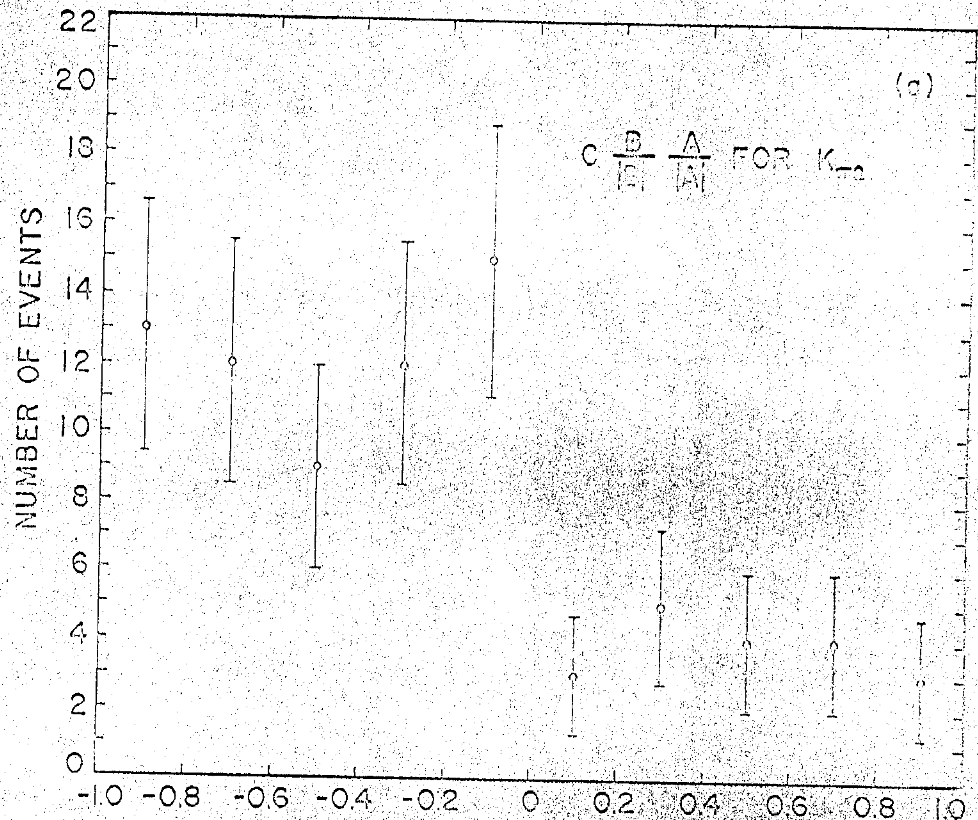
FIGURE CAPTIONS

Fig. 1 (a) Distribution of quantity (defined in text) which exhibits apparent correlation for $K^{+}_{\pi 2}$ events.

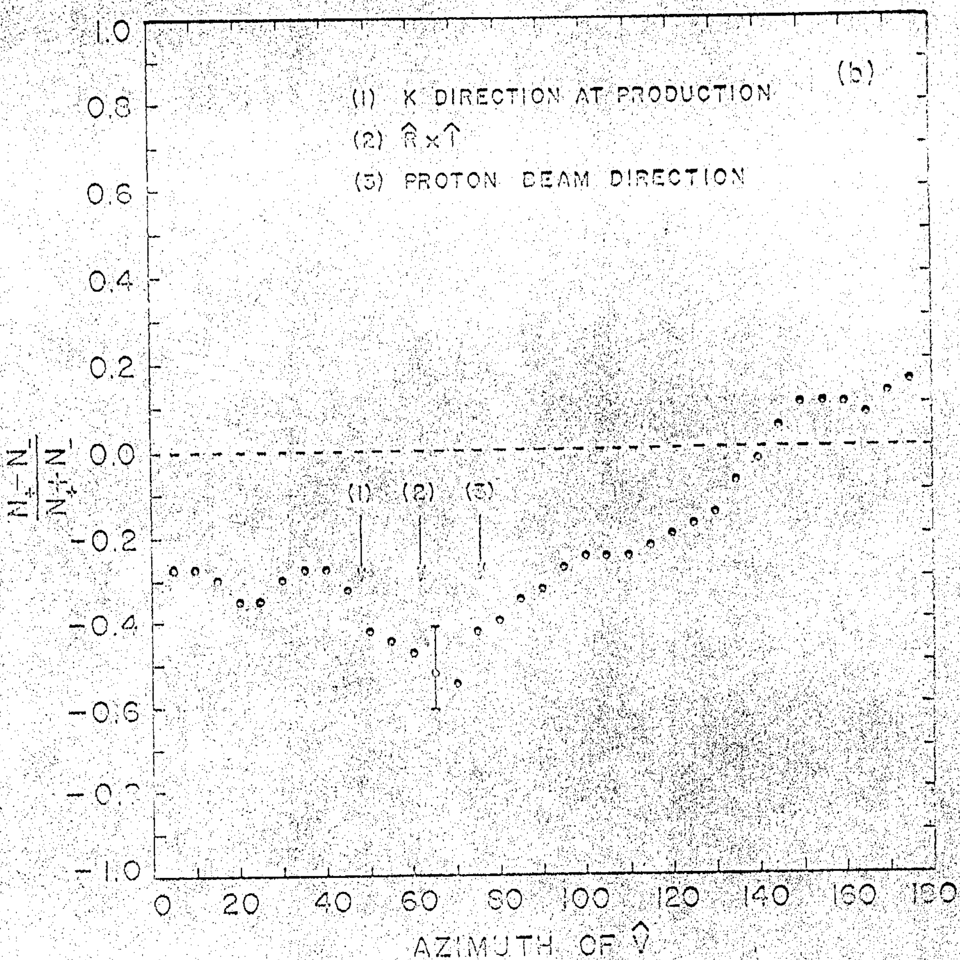
(b) Asymmetry parameter for $K^{+}_{\pi 2}$ events plotted as a function of the azimuth of the unit vector $\hat{V}$ in the plane normal to $\hat{l}$. The stack entrance direction of the K^{+} beam corresponds to 0°.

Fig. 2 Sum distribution of D (defined in text) for τ events and $-D$ for τ' events.

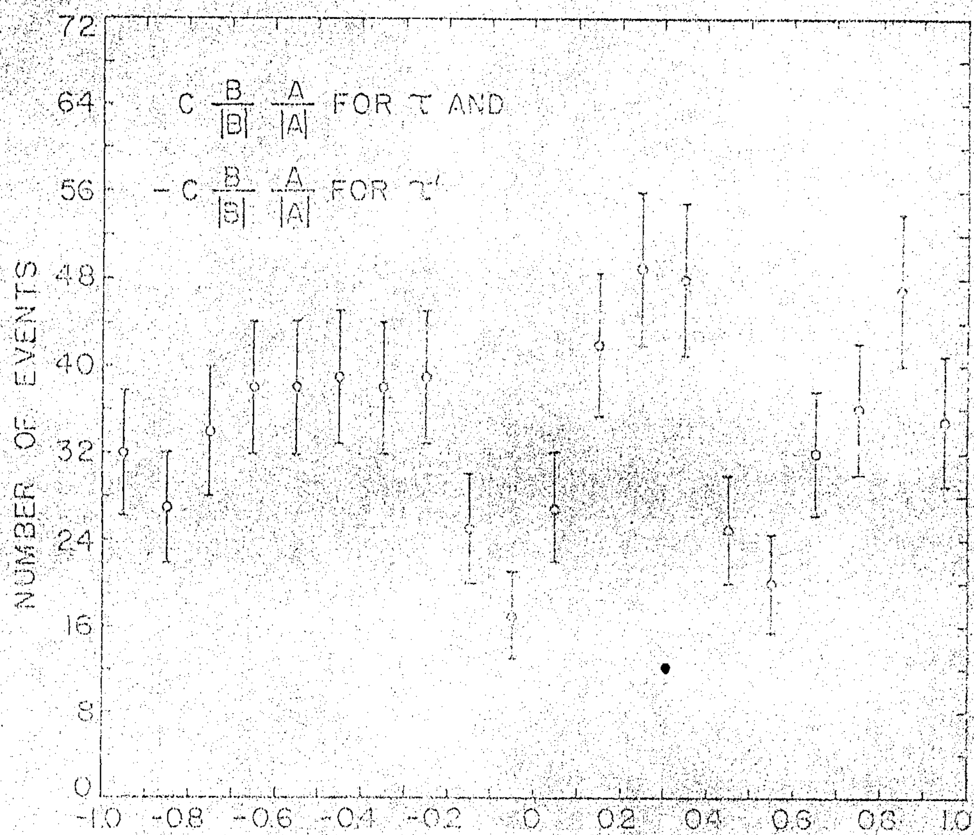


22
20
18
16
14
12
10
8
6
4
2
0
NUMBER OF EVENTS
(a)
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0

MUB-7695


(b)
(1) K DIRECTION AT PRODUCTION
(2) $\hat{R}\times\hat{T}$
(3) PROTON BEAM DIRECTION
(1) (2) (3)
$\frac{N_+ - N_-}{N_+ + N_-}$
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1.0
0 20 40 60 80 100 120 140 160 180
AZIMUTH OF $\hat{V}$

MUB-7696



NUMBER OF EVENTS
0
8
16
24
32
40
48
56
64
72
C B/|B| · A/|A| FOR τ AND
– C B/|B| · A/|A| FOR τ′
-1.0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0

MUB-7697