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# CHARGE ASYMMETRIES IN THE ANGULAR DISTRIBUTION OF $\pi$ AND K MESONS FROM ANTIPROTON ANNIHILATIONS IN FLIGHT

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Presented here are the results of our search for a difference in the angular distributions of negative and positive $\pi$ and K mesons produced in $\bar{p}p$ annihilations, at the center-of-mass momentum of 657±16 Mev/c (1.6 Bev/c in the lab). There have been no direct theoretical predictions for such a difference. The statistical model prescribes an isotropic distribution for mesons of all charges.[1] However, the model of Koba and Takeda[2] assumes that 2 or 3 annihilation pions are emitted from the antiproton and proton clouds. For annihilations in flight, the instantaneous momentum of the pions from the $\bar{p}$ cloud will have a component parallel to the $\bar{p}$ momentum, in addition to their internal momenta. Since the model assumes that the pion cloud does not interact with the annihilation of the cores, it is reasonable to expect this component of the pion momentum to produce an excess of $\pi^-$ over $\pi^+$ in the antiproton direction (forward). An equal excess of $\pi^+$ should also be expected in the direction of the proton (backward). Evidence for such an effect has been scarce prior to this experiment. Angular distributions of pions of both charges from $\bar{p}p$ annihilations in propane at a c.m. momentum of 470 Mev/c (1.05 Bev/c lab) have not shown statistically significant deviation from isotropy.[3] A study of $\bar{p}p$ annihilations into two pions[4] at our momentum is also consistent with an isotropic distribution (8 $\pi^-$ emitted forward, and 12 $\pi^-$ emitted backward). However, annihilations into $K^+K^-$ pairs[4] suggest forward peaking for $K^-$ (8 of the 11 $K^-$ were emitted in the forward direction).[5]

Our analysis was done on two samples of events: (i) 1,620 events of the type $\bar{p}p \rightarrow n\pi$, with $n = 4, 5, \cdots, 8$; and (ii) 287 events of the type $\bar{p}p \rightarrow K+K+n\pi$, with $n = 1, 2, 3$ and 4—in which at least one of the K mesons was observed to decay in the chamber. These events were observed inside a central volume of the 72-in. hydrogen bubble chamber. The average antiproton momentum at the point of interaction was 1.61±0.04 Bev/c (925 Mev kinetic energy) for Sample (i), and for 86% of Sample (ii). The remaining 14% of Sample (ii) was from our run at 1.99±0.05 Bev/c. The experimental conditions have been described previously.[5]

(i) Reactions $\bar{p}p \rightarrow n\pi$. Only annihilations into 4-prongs have been analyzed, in which the identifiable reactions are:

$$\bar{p} + p \rightarrow 2\pi^- + 2\pi^+ + \pi^0 \qquad (1)$$

and

$$\bar{p} + p \rightarrow 2\pi^- + 2\pi^+ . \qquad (2)$$

The abundances of these reactions are about 50% and 10%, respectively. Competing reactions

$$p + p \rightarrow 2\pi^- + 2\pi^+ + n\pi^0 \qquad (3)$$

occur with frequencies of about 32%, 7%, and 1% for $n = 2, 3$, and 4, respectively.

The dynamical fit for each event was done by using an IBM 709 computer program (KICK).[6]

The probability of a background reaction $\pi^- + p \rightarrow$ 4-prongs being wrongly identified as either Reaction (1) or (2) is negligibly small. When the prongs are wrongly transformed into the $\bar{p}p$ c.m. system as pions, there is much too little visible energy and, consequently, several missing $\pi^0$'s are required in order to conserve both momentum and energy. Secondly, the pion contamination in the $\bar{p}$ beam was 36%, and the pion cross section for producing 4-prong stars small, namely, about 2.5 mb compared with 15 mb for $\bar{p}p \rightarrow$ 4-prongs.

Reaction $\bar{p}p \rightarrow 2\pi^- + 2\pi^+ + \pi^0$. We identified 674 cases of Reaction (1). These events satisfied the following conditions: (a) the $\chi^2$ for the hypothesis (1) was $\leq 9$; (b) the value of the missing mass of 4-prongs, interpreted as pions, was within 2.5 standard deviations of 135 Mev; (c) the fitted $\bar{p}$ momentum was $> 640$ Mev/c; and (d) there was no fit for hypothesis (2). Of this sample, 410 events (60%) had $\chi^2 \leq 2.5$ and a missing mass $< 250$ Mev. The still-unresolved systematic errors of our measuring system produce an extended tail in the $\chi^2$ distribution, so that the cutoff value of $\chi^2$ has to be increased generally by a factor of two or three. The angular and momentum distributions of the pions did not show any substantial difference between the samples with $\chi^2 < 2.5$ and $\chi^2 < 9$. Our confidence is increased by the fact that the momentum distribution of $\pi^0$'s agrees very well with that of charged $\pi$'s.

The c.m. angular distribution for Reaction (1) is shown separately for $\pi^-$ and $\pi^+$ in Figs. 1a and 1b. The $\pi^-$ distribution displays a forward peak, whereas that of the $\pi^+$ is backward, contrary to the statistical model. As expected on the basis of C and CP,[7] the distribution of $\pi^+$ appears to be equal, within statistics, to the reflection of the angular distribution of the $\pi^-$'s. To analyze the shape of the distribution, we have reflected the $\pi^+$ distribution about $\cos\theta = 0$ and added it to the $\pi^-$ distribution (Fig. 1c). We have found it convenient (without inquiring into its physical meaning) to express our distribution in terms of the expansion $\Sigma\, a_\ell\, P_\ell\,(\cos\theta)$, where $P_\ell$ are Legendre polynomials and the coefficients are (in units of numbers of pions): $a_0 = 135.3 \pm 2.2$, $a_1 = 24.1 \pm 3.9$, $a_2 = 18.2 \pm 5.1$, $a_3 = 24.4 \pm 6.1$, $a_4 = 19.4 \pm 7.1$, $a_5 = 10.0 \pm 8.9$, $a_6 = -14.3 \pm 8.9$, and $a_7 = -10.2 \pm 10.1$. Note that the sharpness of the distribution makes the fourth order polynomial at least essential for describing the observed effect. The angular distribution of the $\pi^0$'s does not show statistically significant deviations from isotropy. The

momentum distribution of all charged pions agrees well with the phase space distribution, which predicts an average momentum $\langle K \rangle_{av} = 439$ Mev/c. However, for $\pi^-(\pi^+)$ emitted in forward (backward) cone with $|\cos\theta| \geq 0.70$, we observe $\langle K \rangle_{av} = 451 \pm 10$ Mev/c, whereas for the nonforward pions it is $427 \pm 7$ Mev/c. For those events that have simultaneously a $\pi^-$ $(\pi^+)$ in the forward and a $\pi^+$ $(\pi^-)$ in the backward cone, $\langle K \rangle_{av} = 495 \pm 15$ Mev/c $(482 \pm 26)$. It is interesting to note that the hydrodynamic model of multiple-pion production in nucleon-nucleon collisions[8] predicts an increase of pion momenta at small angles.

To determine whether the like pions ($\pi^+\pi^+$ or $\pi^-\pi^-$) have a tendency to be emitted in pairs in the forward peak (Fig. 1c) we have counted the number of Reaction (1) in which both $\pi^-$'s have $\cos\theta \geq 0.80$ ($\leq -0.80$ for $\pi^+\pi^+$). If the probability of finding the second $\pi^-$ in this angular interval were independent of finding the first $\pi^-$ in this interval, then the probability that both $\pi^-$ mesons would be found there would be $1.9 \pm 0.1\%$.[9] We observe simultaneous forward (backward) emission of pairs of $\pi^-(\pi^+)$ in 15 cases of Reaction (1), or $2.2 \pm 0.6\%$.

It has been reported that the angles between the like pions produced in annihilation are smaller on the average than the values predicted by the phase space.[10] Our data confirm this observation. The phase space predicts a value of 1.79 for the ratio $\gamma$ = (number of pion pairs with angle $> 90^\circ$): (number of pion pairs with angle $< 90^\circ$), whereas we observe $\gamma = 1.56 \pm 0.08$ for like pions. To find out whether or not this is caused, in part, by our angular distribution characterized by the sharp peak, we have evaluated $\gamma$ for only those pairs in which at least one $\pi^-$ has $\cos\theta \geq 0.80$ ($\leq -0.80$ for $\pi^+$), and obtained $\gamma = 1.38 \pm 0.13$. For comparison, we have also evaluated $\gamma$ for the pairs in which at least one $\pi^-$ has $\cos\theta \leq -0.80$ ($\geq 0.80$ for $\pi^+$) and obtained $\gamma = 2.05 \pm 0.25$. These two values of $\gamma$ differ by 2.7 standard deviations and indeed indicate that the angular correlations between like pions are influenced by the sharp peak in the forward direction (Fig. 1c).

It will not be possible, however, to obtain a quantitative answer as to the importance of the Bose effect[11] and/or $\pi$-$\pi$ interaction without further extensive studies.

Reaction $\bar{p}p \rightarrow 2\pi^- + 2\pi^+$. On the basis of $\chi^2$ and the missing mass, 136 4-prong events have been identified as Reaction (2). This is a 4-constraint case, and the maximum acceptable $\chi^2$ was taken to be 36; about 65% of these events have $\chi^2 < 10$. The angular distribution of $\pi^-(\pi^+)$ shows a forward (backward) peak (Fig. 1d).

Reaction $\bar{p}p \rightarrow 2\pi^- + 2\pi^+ + n\,\pi^0$. The remaining 810 events, which did not fit either Reaction (1) or (2), were assumed to be Reaction (3). However, this sample contains an estimated 16% of annihilations into K mesons, Reactions (4 to 7) (see below), in which K mesons have not decayed in the chamber. Because we transform our events into the c.m. system by ascribing pion mass to all charged prongs, the resultant c.m. angle will be wrong for these events. Also, this sample contains 4-prongs produced by $\pi^-$ in the antiproton beam, whose contribution could be as high as 5%. In spite of this background, the angular distribution of $\pi^-$ and $\pi^+$ exhibits features similar to the ones of Reactions (1) and (2) (Fig. 1e). The average momentum is 369±9 and 332±5 Mev/c for forward and nonforward pions, respectively.

(ii) Reactions $\bar{p}p \rightarrow \bar{K}+K+n\pi$. Of the 287 $K\bar{K}n\pi$ events, 135 were V-two prong or V-4 prong events having a $K^+\bar{K}^0$ or $K^-K^0$ pair from the reactions:

$$\bar{p}p \rightarrow K^+ + \pi^- + \bar{K}^0 + n_1\pi^0 , \tag{4}$$

$$\bar{p}p \rightarrow K^+ + \pi^+ + 2\pi^- + \bar{K}^0 + n_2\pi^0 , \tag{5}$$

$$\bar{p}p \rightarrow K^- + \pi^+ + K^0 + n_3\pi^0 , \tag{6}$$

and

$$\bar{p}p \rightarrow K^- + \pi\pi^- + 2\pi^+ + K^0 + n_4\pi^0 . \tag{7}$$

As can be seen from the nature of Reactions (4 to 7), this sample contains a variety of types of events from the point of view of the fitting procedure, with the number of constraints 1, 3, and 4. Clearly, each of these requires a separate set of criteria for identification. We shall give only a general outline: (a) the $\chi^2$ distribution for each type of event agreed well with the expected distribution when it was divided by 3; (b) the missing mass distributions were used to determine the number of neutral particles ($\pi^0$'s, or $K^0$ plus $\pi^0$'s) associated with each event; and (c) the data were examined and found to be reasonably free of biases by looking at azimuthal distributions of events in the bubble chamber, their spatial distribution along the chamber, and the distribution of decay times for $K^0$(or $\bar{K}^0$). The events were not generally ambiguous as to the number of missing neutral particles. For most of the events, only one of the K mesons was observed to decay within the chamber. Some events are ambiguous as to which particle is the second K meson. The detailed procedure for the identification and disposition of the ambiguities of these events is given elsewhere.[12] The angular distribution of both $K^-$ and $\pi^-$ ($K^+$ and $\pi^+$) has exhibited a forward (backward) peak in a fashion similar to the ones of Reactions (1 to 3), as shown in the histograms in Figs. 2a and 2b.

Our angular distribution indicates a possibility that two different annihilation mechanisms are operative: the statistical one, which is dominant and produces an isotropic angular distribution; and a dynamical mechanism responsible for the forward peak. Whereas the observed forward-to-backward ratio F/B is consistent with the model of Koba and Takeda,[13] it is not clear whether the fact that kaons show similar angular distribution features is consistent with that model, because it has never been extended in all its manifestations for the annihilations in flight.

The very recent data on antineutron-proton annihilations at our momentum indicate a possible excess of $\pi^+$ in the direction of the proton.[14]

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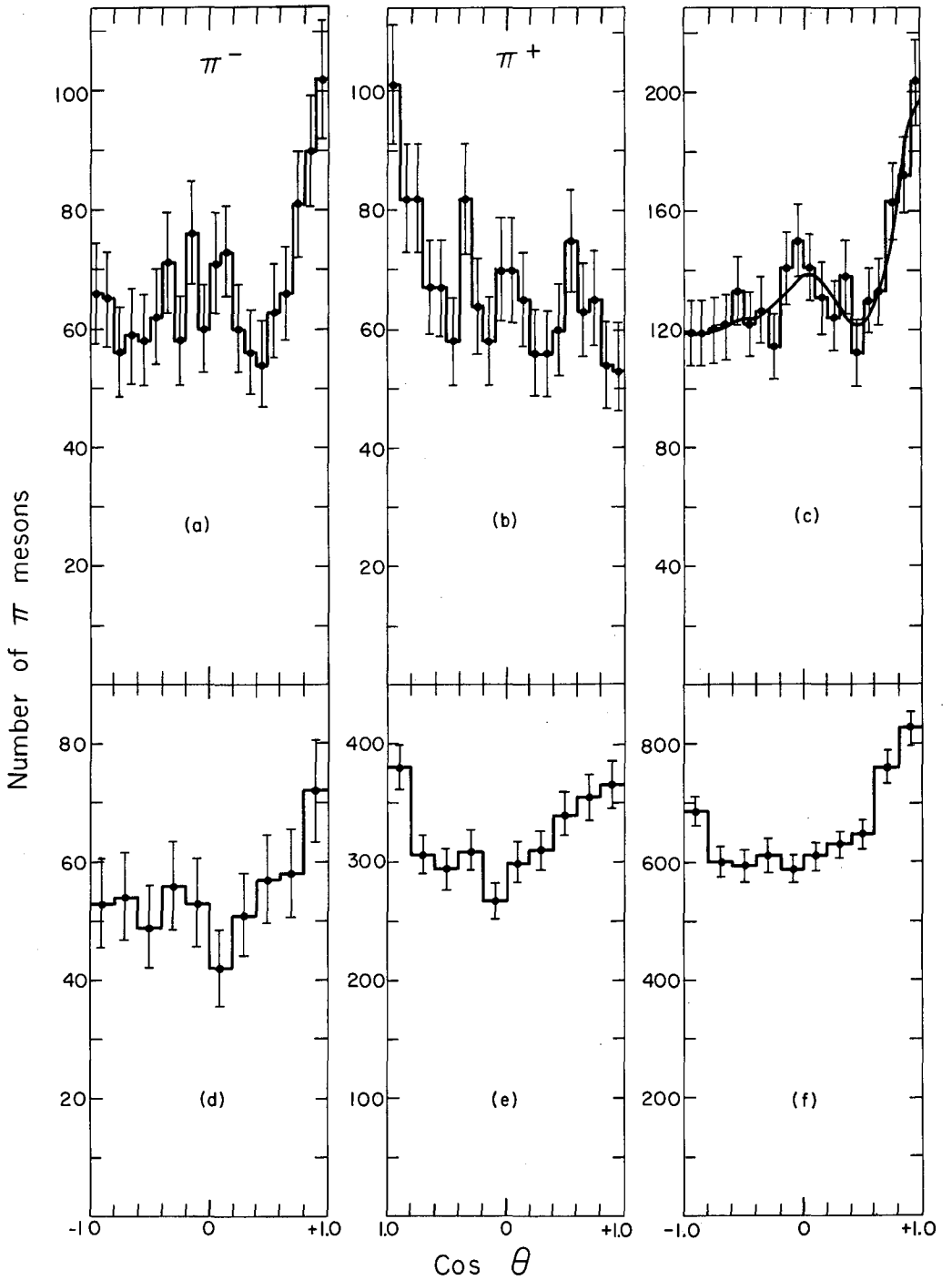
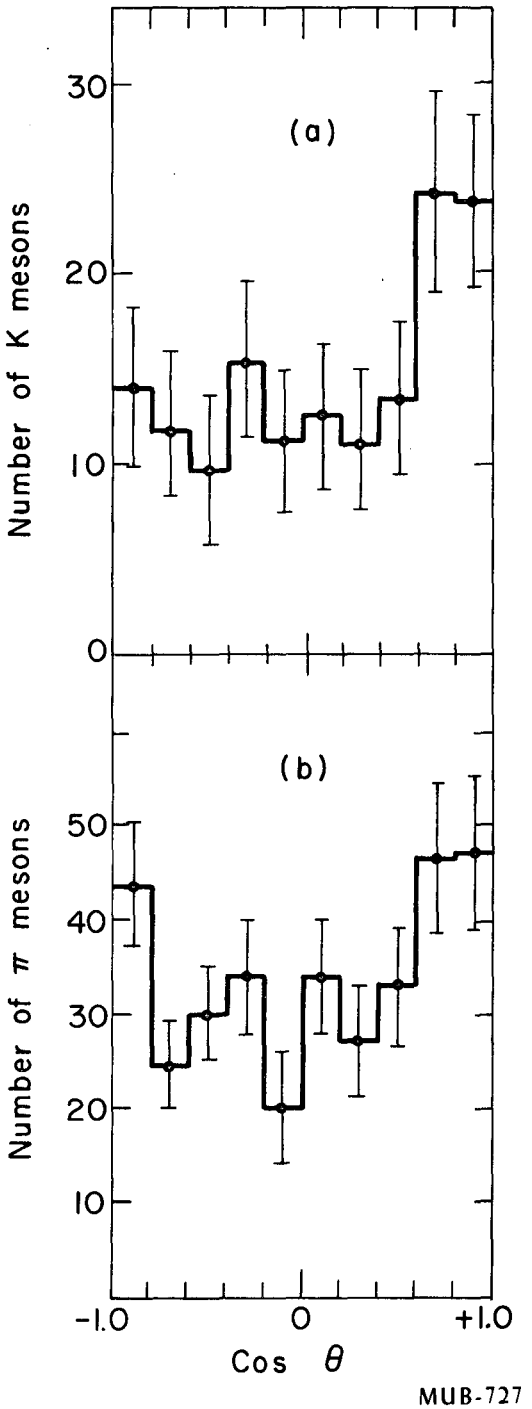
## LEGENDS

Fig. 1. Histograms of c.m. angular distribution of pions from Reactions (1 to 3): (a) and (b): $\pi^-$ and $\pi^+$ from Reaction (1); (c): combined distributions (a) plus reflected (b); (d); $\pi^-$ and reflected $\pi^+$ from Reaction (2); (e): negative and reflected positive prongs which did not fit Reactions (1) and (2); and (f): combined data (c), (d), and (e). The forward-to-backward ratio, F/B, is 1.17±0.04, 1.06±0.09, 1.08±0.04 and 1.13±0.03 for distributions (c), (d), (e), and (f), respectively.

Fig. 2. Histograms of (a) combined angular distributions of $K^-$ and reflected $K^+$ from Reactions (4 to 7); and (b) $\pi^-$ and reflected $\pi^+$ from Reactions (4 to 7). The F/B ratio is 1.37±0.18 and 1.24±0.15 for distributions (a) and (b), respectively.


π⁻
π⁺
(a)
(b)
(c)
(d)
(e)
(f)
Number of π mesons
Cos θ
-1.0
0
+1.0
1.0
MUB-728


(a)
(b)
Number of K mesons
Number of π mesons
30
20
10
0
50
40
30
20
10
-1.0
0
+1.0
Cos θ

MUB-727