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PION-PION CORRELATIONS IN ANTIPROTON ANNIHILATION EVENTS*

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We have observed angular correlation effects between pions emitted from antiproton annihilation events. This experiment was carried out with a separated antiproton beam[1] of momentum $p_{\bar{p}} = 1.05$ Bev/c. A total of 2500 annihilation events were observed in 20 000 pictures taken with the Lawrence Radiation Laboratory 30-in. propane bubble chamber.

Pion pairs formed by the charged pions emitted in an antiproton-annihilation event can be considered in two groups: viz., like pairs (in the isotopic-spin state $I=2$) and unlike pairs (in the isotopic-spin states $I=0, 1$, or 2). We searched for correlation effects in these separate groups. Our results show that the distribution of the angles between pions of like charges is strikingly different from the distribution of the angles between pions of unlike charges. The angles between pion pairs were computed in the center of mass of the antinucleon-nucleon system.[2] The results shown in Fig. 1 were obtained from the analysis of the "hydrogenlike" events in which four and six charged pions, respectively, are emitted. We define as "hydrogenlike" those events giving rise to an equal number of positive and negative pions. Events showing visible evaporation prongs are excluded from this sample. The curves shown in Fig. 1 were calculated on the basis of the statistical model, expressed in the Lorentz-invariant phase-space[3] (LIPS) form, for pion production from a nucleon-antinucleon annihilation. This model imposes energy and momentum conservation, but no other constraints. The distribution of the pion-pair angles θ_{12} for an annihilation into n pions of mass μ is[4]

$$\phi_n(\cos\theta_{12}) = \iint p_1 p_2 F_{n-2}(W''^2)\, d\omega_1 d\omega_2,$$

with integration limits from $\omega_1 \geq \mu$, $\omega_2 \geq \mu$ to max

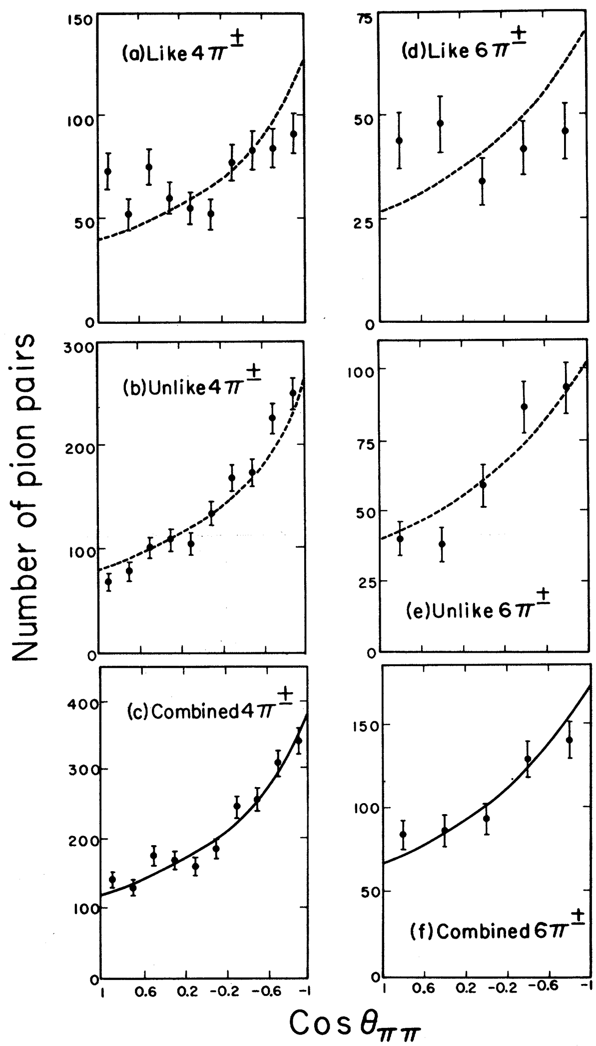

FIG. 1. Distribution of angles between pion pairs as a function of $\cos\theta_{12}$. The curves correspond to calculations on the Lorentz-invariant phase-space (LIPS) model. The deviations of the experimental distribution from the LIPS model are discussed in the text.

Table I. The ratio γ for like and unlike pion pairs and for the Lorentz-invariant phase-space (LIPS) model.[a]

	Like pions		Unlike pions		All pions combined		Statistical model
$N_{\pi^\pm}$	No. of pairs	γ	No. of pairs	γ	No. of pairs	γ	γ
4	702	1.23 ± 0.11	1404	2.06 ± 0.12	2106	1.72 ± 0.08	1.74
6	214	1.06 ± 0.15	318	1.91 ± 0.23	532	1.50 ± 0.13	1.60

[a]The ratio γ is the number of pion-pair angles greater than 90° compared to those smaller than 90°. The errors quoted are the standard deviations based on the number of pairs observed.

values given by $W''^2=(n-2)^2\mu^2$. Here we define

$$W''^2=(W-\omega_1-\omega_2)^2-(\vec{p}_1+\vec{p}_2)^2;$$

$F_{n-2}(W''^2)$ is the Lorentz invariant phase space for $(n-2)$ pions, W is the total energy in the center of mass of the antinucleon-nucleon system, and we have

$$\cos\theta_{12}=\vec{p}_1\cdot\vec{p}_2/|p_1||p_2|.$$

To compare with the experimental distributions for events with $n_\pm$ charged pions, averages over ϕ_n values with $n\geq n_\pm$ are required. This takes into account the presence of additional neutral pions in the annihilation. We have used the frequency distribution of the pion multiplicity in annihilation events, as reported elsewhere,[5] for computing these averages.

In Table I we have expressed the distribution of pair angles in terms of the ratio, γ, of the number of pion-pair angles greater than 90° to the number smaller than 90°. As can be seen from Fig. 1 (c) and (f), the pion-pair distribution of like and unlike pions combined agrees very well with the LIPS model.[6] The distribution of angles between pions [Fig. 1 (a) and (d)] deviates distinctly from the LIPS model. The γ_{like} values for $4\pi^\pm$ and $6\pi^\pm$ differ from γ_{LIPS} by 5 and 3.4 standard deviations, respectively, in the direction of greater isotropy. The distribution of pion-pair angles for unlike pions appears to be slightly more asymmetric than the LIPS model predicts. In this case, the values of γ_{unlike} are 2 and 1.5 standard deviations, respectively, removed from the value given by the LIPS model.

We have also computed the invariant quantity

$$Q_{12}^2=(\omega_1+\omega_2)^2-(\vec{p}_1+\vec{p}_2)^2,$$

for each pion pair. Here Q is the total energy in the center of mass of the pion-pion system. These distributions are given in Fig. 2. Within statistical limits no significant difference between the Q^2 distribution of like and unlike pion pairs has been observed. Curves shown in Fig. 2 were also computed on the basis of the LIPS statistical model. The experimental Q^2 distributions show no marked

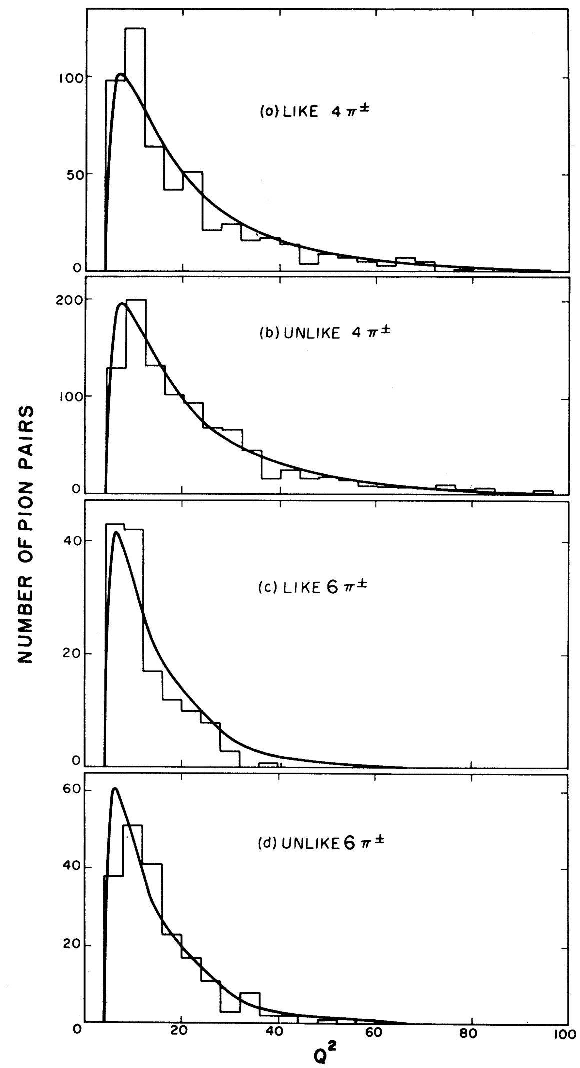

FIG. 2. The distribution of Q^2, the square of the total energy in the center of mass of the pion-pion system in units of μ^2.

deviation from the calculated curves.

In view of the remarkable agreement of the combined data with the LIPS model, we consider this model to be a good description of the over-all physical situation. We ascribe the deviations observed in the like and unlike pion pairs to the presence of additional pion-pion correlations.

It should be noted that in order to retain the over-all agreement with the LIPS model, a correlation effect present in either of the two distributions must reflect on the other distribution. The effect we have observed clearly indicates the need for a refinement of the LIPS model.

Work is in progress to investigate modifications of the LIPS model by means of correlation functions which may account for the observed pion-pion correlations.[7] These correlation functions involve the radius R of the interaction volume as a parameter, and may enable one to determine its value. The role of such correlations will be to effectively enhance specific states. In this connection the recently suggested resonance of the 2π system with $J=1$, $I=1$ may be of particular interest.[8]

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PROTONS FROM THE SUN ON MAY 12, 1959

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In the past year evidence has been accumulating that high-energy nucleons arrive at the earth following solar disturbances.[1-3] The characteristics of the arrival of these beams from the sun are the enhanced cosmic noise absorption on the polar cap, the arrival of particles at the top of the atmosphere, followed by a Forbush decrease in cosmic rays at sea level.

We report here the most spectacular such event which has occurred to date, in which ion chambers, Geiger and scintillation counters, and photographic emulsions were exposed above Minneapolis at a pressure altitude of 10 g/cm^2 throughout the period of enhanced intensity. We previously reported an event of this type in which the intensity of the integral flux of protons at the top of the atmosphere in a vertical direction was increased by about a factor of two, on March 26, 1958.[2] In the present event, the integral flux of particles at the top of the atmosphere increased by approximately a factor of 1000 above that of cosmic rays, and the composition of the incoming beam as observed at 10 g/cm^2 atmospheric depth was essentially pure hydrogen. The flux of alpha particles and heavy nuclei was not increased and corresponds to the normal cosmic-ray flux at solar maximum. However, if the solar-injected heavy particles had the same rigidity spectrum as the protons we observe, the atmospheric cutoff would not allow their detection at 10 g/cm^2 atmospheric depth. The abundance of relativistic protons and high-energy electrons is less than 10% of the flux of solar protons.

The energy spectrum of the incoming particles has been measured in photographic emulsions and is well represented by a differential kinetic energy spectrum of the form $n(E)dE = KE^{-4.8}dE$ in the measured energy range 110 Mev $< E <$ 220 Mev. The corresponding integral rigidity spectrum is $N(>R) = 7500/R^{6.8}$ with R expressed in Bv and $N(>R)$ given in protons/m^2 sec steradian.