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MULTIPLICITY IN HADRON PRODUCTION BY $e^+e^-$ COLLIDING BEAMS.

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# MULTIPLICITY IN HADRON PRODUCTION BY $e^+e^-$ COLLIDING BEAMS

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The average multiplicities $\langle n_c \rangle$ and $\langle n \rangle$, of charged and charged-plus-neutral pions produced in $e^+e^-$ collisions, have been determined for total center-of-mass energies ranging from 1.2 to 2.4 GeV. No appreciable multiplicity variation is observed over this energy range, where the mean values $\langle \bar{n}_c \rangle = 3.3^{+0.3}_{-0.2}$ and $\langle \bar{n} \rangle = 4.4^{+0.4}_{-0.2}$ are found.

Multi-hadron production by $e^+e^-$ colliding beams has been recently investigated†1 with Adone, the Frascati storage ring, at total C.M. energies $E_+ + E_- \equiv 2E \equiv \sqrt{s}$ ranging from 1.2 to 2.4 GeV. It has been shown in particular that in this energy range the produced hadrons are mostly pions [2], so that the selected channels can be written as

$$e^+e^- = \tfrac{1}{2} n_c \pi^+ + \tfrac{1}{2} n_c \pi^- + n_o \pi^0 \qquad (1)$$

with $n_c \geqslant 2, n_o \geqslant 0, n_c + n_o > 2$. It should be noticed that the energy interval 1.2–2.4 GeV starts well above the well-established vector meson resonances $(\rho, \omega, \varphi)$ and extends to energies near the threshold for inelastic production of baryon-antibaryon pairs. Over this energy interval we have now determined the average multiplicities for charged plus neutral pions, $\langle n \rangle = \langle n_c + n_o \rangle$, and for charged pions alone, $\langle n_c \rangle$.

Thus relevance of knowing the energy dependence of the pion multiplicity for the understanding of reaction (1) has been pointed out by several authors on theoretical grounds [3–8]. For example in the so-called Bjorken limit [9] such an energy dependence can be directly related to the energy dependence of the annihilation structure functions, which are in turn related to the inclusive cross section in multihadron production [10].

The results reported in the present letter show that the pion multiplicity is essentially constant over the energy range explored.

The apparatus used in the experiment has already been described in ref. [2]. It will be sufficient to recall here that it is based on optical-spark chamber and counter-electronic techniques.

The cross sections for the various channels of reaction (1) have been derived in ref. [2] assuming that multihadron production occurs according to invariant phase space. These cross sections have now been recalculated taking into account the evidence for a $\rho'$ meson production [2, 11] and its subsequent decay into four pions through a probable $\rho^0 \epsilon^0$ state [12]. The new cross sections are reported in table 1, where the average charged multiplicity $\langle n_c \rangle$ and the average total multiplicity $\langle n \rangle$ are also given (last two columns).

†1 For a summary of the most recent results on multihadron production obtained by the experimental teams at Adone, we refer the reader to refs. [1, 2, 13, 16].

Table 1

| Channel 2E (GeV) | Cross sections (nb): $\pi^+\pi^-\pi^0\pi^0$ ($n_c = 2$, $n_o = 2$) | $2\pi^+2\pi^-$ ($n_c = 4$, $n_o = 0$) | $2\pi^+2\pi^-\pi^0$ ($n_c = 4$) ($n_o = 1$) | $2\pi^+2\pi^-2\pi^0$ ($n_c = 4$, $n_o = 2$) | $2\pi^+2\pi^-$ + +1 or $2\pi^0$ ($n_c = 4$, $n_o = 1$–2) | $3\pi^+3\pi^-$ ($n_c = 6$, $n_o = 0$) | $\sigma \geqslant 4c$ ($n_c \geqslant 4$, $n_o > 0$) | $\sigma_{tot} = \sum_{n_c n_o} \sigma(n_c n_o)$ | Multiplicity: $\langle n_c \rangle$ | $\langle n \rangle$ | Syst. error of $\langle n \rangle$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 21 ± 15 | ( 3±3)±3 | | | (5±5)± 6 | <1 | (8±2)± 6 | (34±2)±16 | $2.5^{+0.9}_{-0.5}$ | $3.7^{+1.4}_{-0.7}$ | 0 |
| 1.4 | | | | | | | 31 ± 15 | | | | |
| 1.5 | 20 ±11 | (17±3)±3 | 6 ±7 | 16 ± 8 | 22±7 | 3±3 | 42 ± 9 | 66±9 | 3.4 ± 0.4 | 4.5 ±0.7 | +0.7 |
| 1.6 | 23 ± 10 | 16 ± 6 | | | 21±10 | | 37 ± 12 | | 3.2 ± 0.4 | | |
| 1.65 | | | | | (18± 4)± 9 | <3 | (33 ±4) ±10 | | | | |
| 1.7 | | 10 ± 7 | | | | | | | | | |
| 1.77 | | | | | | | 24±10 | | | | |
| 1.9 | 13 ± 5 | 5.5±2 | 5 ±3 | 7 ± 3 | 11± 3 | 3.5±1.5 | 19± 3 | 36± 5 | $3.6^{+0.4}_{-0.7}$ | $4.5^{+1.1}_{-0.3}$ | +0.7 |
| 2.0 | | | | | | | 21±11 | | | | |
| 2.1 | 15.5± 4 | 1.5±1 | 9.5±3 | 3 ± 2 | 12± 3 | 3.5±1 | 16± 3 | 36±4 | 3.1±0.5 | $4.6^{+0.7}_{-0.3}$ | +0.7 |
| 2.4 | | <4 | $10^{+7}_{-4}$ | 3 ± 4 | 13± 4 | 4 ± 2 | 16± 4 | | $3.2^{+0.7}_{-0.3}$ | $4.6^{+0.6}_{-0.4}$ | +0.7 |

Where two errors are reported for the cross-sections, the first, in parenthesis, is the systematic error and the second is the statistical one. For the meaning of the systematic error of $\langle n \rangle$ (last column) see text.

In figs. 1 and 2 the quantities†2 $\langle n \rangle$ and $\langle n_c \rangle$ are reported as a function of the total center-of-mass energy squared, $s$. The multiplicity values at $\sqrt{s}$ = 3 GeV and $\sqrt{s}$ = 4 GeV, as recently reported by other groups [13, 14]†3 are also given for completeness†4 in the same figures. In deriving our results the following assumptions have been made:

i) Over the energy range explored, the maximum number of produced pions is six. As mentioned in [2] this assumption is supported by the observation that proton-antiproton annihilation at rest occurs with an average multiplicity 5.0 ± 0.15†5, a multiplicity greater than 6 occurring in less than 10% of the cases [e.g. 15].

ii) The channel $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ is dominant among those with $n_c$ = 2 and $n_o \geqslant 1$.

iii) The final state $\pi^+\pi^-\pi^+\pi^-$ is reached through an intermediate $\rho^0\epsilon^0$ state [11], i.e.

$$e^+e^- \to \rho^0\epsilon^0 \to \pi^+\pi^-\pi^+\pi^- .$$

iv) The final state $\pi^+\pi^-\pi^0\pi^0$ is produced as an incoherent sum of $\rho^0\epsilon^0$ and phase space decay mechanisms, assuming a branching ratio

$$\frac{\sigma(e^+e^- \to \rho^0\epsilon^0 \to \pi^+\pi^-\pi^0\pi^0)}{\sigma(e^+e^- \to \rho^0\epsilon^0 \to \pi^+\pi^-\pi^+\pi^-)} = \frac{1}{2}$$

on the basis of isospin conservation.

v) Production according to invariant phase space is dominant for processes with more than four pions in the final state.

Assumptions ii) to v) have only a small influence on the derived multiplicity values. Only assumption i) has an appreciable influence which has been evalu-

†2 These multiplicities are defined in an obvious way. For example $\langle n \rangle$ is related to the partial cross sections $\sigma(n_c, n_o)$ for producing $n_c$ charged and $n_o$ neutral pions by $\langle n \rangle = [\sum_{n_c,n_o}(n_c+n_o) \cdot \sigma(n_c,n_o)] / \sum_{n_c,n_o}\sigma(n_c,n_o)$. The values of $\sigma(n_c, n_o)$ for different total energies ($2E = \sqrt{s}$) are reported in table 1.

†3 The quoted value of $\langle n_c \rangle$ at $\sqrt{s}$ = 3 GeV has been presented by Silvestrini [1]. In this review paper also data have been presented from the same group at lower energy. These results completely agree with our data reported in fig. 2.

†4 We wish to thank the members of these groups for permission to quote these unpublished data.

†5 We point out that this number is close to the value of $\langle n \rangle$ found by us (fig. 1) in $e^+e^-$ annihilation at the same C.M. energy. The same is true also for the charged multiplicity, $\langle n_c \rangle_{p\bar{p}}$ = 3.05 ± 0.10 [15] (compare with fig. 2). For the sake of completeness we add that the energy dependence of $(\langle n_c \rangle)_{p\bar{p}}$ can be expressed as [15] $(\langle n_c \rangle)_{p\bar{p}} = a + b\sqrt{s}$, with $a$ and $b$ again close to the values given in fig. 2.

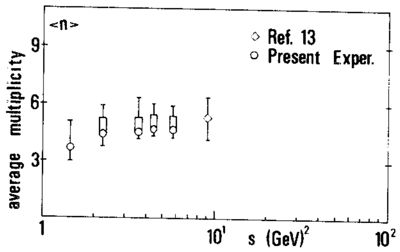


Fig. 1. Average multiplicity, $\langle n \rangle$, versus total energy squared, $s$. The boxes indicate systematic errors originated from the neglected states with more than six pions (see text).

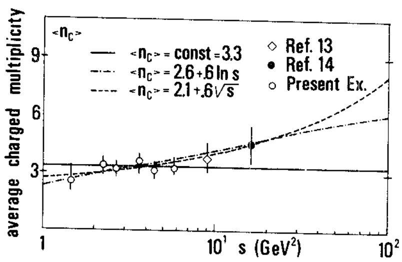


Fig. 2. Average multiplicity, $\langle n_c \rangle$, versus total energy squared $s$. Experimental results of refs. [13, 14] are included. The curves refer to three possible parametrizations (see text).

ated under the hypothesis that, when energetically possible, a 10% of the total cross section is due to final states with more than six pions. This hypothesis is in accordance with the above mentioned result on $p\bar{p}$ annihilation at rest [15]. The resulting multiplicity variations are reported in table 1 as systematic errors.

It is seen from table 1 that over the energy range explored $\langle n \rangle$ and $\langle n_c \rangle$ are apparently constant. Unfortunately this result cannot be directly compared with current theoretical predictions based on the asymptotic scaling law. As a matter of fact we have some arguments which rather suggest that the asymptotic region is not yet attained at Adone's energies:
a) most of processes (1) have thresholds in the neighbourhood of $\sqrt{s} = 1$ GeV, i.e. near the energy region explored in this experiment; b) it is not unlikely that processes (1) are mainly caused by some new resonances, as suggested by the probable existence of the $\rho'$ meson [2, 11]; c) there is some indication [13, 14, 16] that, contrary to the scaling predictions, the ratio $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ increases with increasing $s$, for $\sqrt{s} > 2.4$ GeV. Because of these arguments our result of a nearly constant multiplicity might be understood as an effect of a compensation between the opening of new channels and the decrease of the contributions of previous channels, as $s$ increases.

Using the higher energy results already quoted [13, 14] we have parametrized $\langle n_c \rangle$ according to the functions $\langle n_c \rangle = a + b \cdot \ln s$ and $\langle n_c \rangle = a + b\sqrt{s}$. These functions have the behaviour predicted by some models [3–8] which do not necessarily require scaling. The best fits to the experimental points are

$$\langle n_c \rangle = (2.6 \pm 0.5) + (0.6 \pm 0.3) \cdot \ln s$$

$$\langle n_c \rangle = (2.1 \pm 0.7) + (0.6 \pm 0.3)\sqrt{s}.$$

Of course the distinction between the quoted energy dependences is outside the present experimental possibilities.

The mean values of our experimental points over the energy interval 1.2 – 2.4 GeV are: $\langle \bar{n} \rangle = 4.4^{+0.4}_{-0.2}$; $\langle \bar{n}_c \rangle = 3.3^{+0.3}_{-0.2}$.

The evaluated +0.7 systematic error indicated in table 1 should be added to the above statistical error relative to $\langle \bar{n} \rangle$.

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