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Inelastic Two-Prong Interactions of 18 GeV/c Pions in Propane Bubble Chamber.

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Summary. — This work concerns the study of 18 GeV/c π^--mesons interactions in which only one or two pions are produced. The results give support to the assumption that for these events the one-pion exchange is the dominant process. A tentative interpretation of the pion-pion vertex structure is also given.

1. – Introduction.

The purpose of this work is to analyse the single and double production of π-mesons by 18 GeV/c π^--mesons on protons. The possible reactions are the following:

$$\pi^- + p \to \pi^- + p + \pi^0 \tag{1}$$

$$\to \pi^- + p + \pi^0 + \pi^0 \tag{2}$$

$$\to \pi^- + n + \pi^+ \tag{3}$$

$$\to \pi^- + n + \pi^+ + \pi^0 . \tag{4}$$

This analysis has been suggested by experimental [1,2] and theoretical [3-6]

(1) D. R. O. MORRISON: *Aix-en-Provence International Conference on Elementary Particles*, Vol. 1 (1961), p. 407.

(2) G. COCCONI, A. N. DIDDENS, E. LILLETHUN and A. M. WETHERELL: *Phys. Rev. Lett.*, **6**, 231 (1961).

(3) S. D. DRELL and K. HIIDA: *Phys. Rev. Lett.*, **7**, 199 (1961).

(4) M. L. GOOD and W. D. WALKER: *Phys. Rev.*, **120**, 1857 (1960).

(5) F. SALZMAN and G. SALZMAN: *Phys. Rev.*, **120**, 599 (1960).

(6) S. D. DRELL: *Aix-en-Provence International Conference on Elementary Particles*, Vol. **2** (1961), p. 125.

works on peripheral models for inelastic high-energy processes. In fact, the selection of low multiplicity jets gives a sample of π^- interactions suitable for comparison with theoretical predictions; moreover, as we shall explain in more details in the following sections, the experimental material at our disposal allows us to detect with good efficiency also the neutral mesons and therefore we can hope to obtain, in principle, a complete description of this particular type of high-energy interaction.

2. – Exposure data and scanning criteria.

This work has been done utilizing about 7 000 photograms of the Ecole Polytechnique propane bubble chamber, exposed at CERN's protosynchrotron [7].

The useful volume of the chamber was (100 cm $\times$ 50 cm $\times$ 50 cm), the liquid composition 86 % propane and 14 % freon in volume, and the magnetic field 17.5 kG. The exposition was made to a beam of π^--mesons of momentum (18.1 ± 2 %) GeV/c and having a contamination of ~ 4 % ($\mu + e$) and ~ 1 % ($K^- + p$). In this work we assumed that all the observed interactions were produced by the incident π^--mesons [*].

We know that, with the mixture used for this exposure, the percentage of interactions on free protons is ~ 27 % of all interactions. During the scanning, we selected the « hydrogen-like » interactions with the following criteria:

a) Total charge = 0.

b) The events with a slow proton were considered only if the range of the proton was $\geqslant 2$ mm and if the angle of the proton with the primary direction was $\leqslant 90°$.

The same criteria hold for the selection of « neutron-like » interactions with the only difference that the total charge must be -1.

The results of this scanning selection are:

« hydrogen-like » interactions: 43 % of the total number of interactions;

« neutron-like » interactions: 16 % of the total number of interactions.

(*) The contamination has been taken into account in the evaluation of cross-sections.

(7) Beam and run by C. BAGLIN, H. BINGAM, M. BLOCH, D. DRIJARD, A. LAGARRIGUE, P. MITTNER, A. ORKIN LECOURTOIS, P. RANÇON and A. ROUSSET (Ecole Polytechnique, Paris); B. DE RAAD, R. SALMERON and R. VOSS (CERN, Geneva). The construction and properties of the chamber are described by M. BLOCH, A. LAGARRIGUE, P. RANÇON and A. ROUSSET: *Rev. Sci. Instr.*, in press.

If we consider the first of these figures, and take into account that 27 % of all the interactions are on free protons, we obtain that 16 % of all the interactions are glancing collisions on a bound proton in which no visible energy is given to the other nucleons of the nucleus. This is in perfect agreement with the percentage of « neutron-like » interactions.

In this way we evaluate that if we select the « hydrogen-like » interactions with the above explained criteria, we shall have a sample containing 63 % of interactions on free protons and 37 % of glancing collisions on bound protons. This is a drawback of the mixture used in this exposition; on the other hand, we have the advantage that it is possible to detect the π^0-mesons owing to the high conversion power. The radiation length in the chamber is 54 cm; the probability of observing one γ, if two γ's are produced, is of order of $(60 \div 65)\%$.

3. – Measurements and selection of the events.

We limited our analysis to two-prongs stars whose origin was located in a fiducial region between 10 and 50 cm from the beam entrance window; this has been done in order to have a path of at least 50 cm inside the chamber for the most energetic tracks that are always emitted in the forward direction.

Charged prongs have been measured in order to determine their momentum and angle of emission; moreover momentum and line of flight of γ-rays correlated with each interaction were determined. The tracks have been measured with a co-ordinatograph, and the data recorded on punched cards; the spatial reconstruction was made by a ΓET Olivetti Bull computer using a program elaborated by the Ecole Polytechnique group; the results of this first program were used as input for a second program on a IBM computer, which calculates the kinematical quantities and the momentum balance in the center-of-mass system.

Ionization measurements were also performed on positive tracks of momentum < 1.5 GeV/c by the mean gap length method. These measurements, as well as range or residual range and δ-ray criteria, allowed us to identify proton tracks up to 1.2 GeV/c.

Our problem is to select among the analysed stars with two charged prongs the inelastic ones with at most three pions emitted.

In order to reject the inelastic π^--p scattering, the kinematics of all two-prong events without γ-rays and with a recognized proton has been carefully studied in the laboratory system. The kinematical analysis is based on the angles of both tracks and on the momentum of the proton only, owing to the difficulty of obtaining a precise determination of very high momenta. As we have a 37 % of interactions on bound protons, in doing this kinematical analysis, we have taken into account the effect of the Fermi momentum on the angle-momentum-dependence of the proton in the laboratory system.

The number of two-prong interactions selected during the scanning was 205; 47 of these have been recognized as elastic ones. These figures cannot be used to give an evaluation of the elastic cross-section because of the limitation on the range of the proton made during the scanning.

Furthermore, 32 events were rejected because it has been possible to establish that more than three pions were emitted in these interactions. The π^+-mesons were identified by ionization measurements or residual range up to 1.2 GeV/c; above 1.2 GeV/c all the positive tracks were assumed to be pions. The π^0-mesons were identified by the analysis of the γ-rays; from angular and momentum measurements it was almost always possible to decide if two γ-rays belonged or not to the same π^0-meson.

We think that the sample of 126 events selected in this way can be ascribed with a high degree of confidence to reactions of the types (1), (2), (3), (4) (see Introduction).

4. – Experimental results on P_T^* and P_L^*.

Each one of the 126 events selected in the way described in the foregoing sections, has been transformed in the centre of mass of the π^--p system. The results of momentum distribution are collected in Fig. 1 and 2.

As one can see, the distribution of the transverse momentum P_T^* (Fig. 1) is nearly the same for positive and negative tracks, and it shows a high probability for the two charged particles being emitted in the c.m. system with P_T^* low with respect to the maximum of 2.8 GeV/c. The mean values of transverse momentum are:

$$\overline{P}_T = 0.425 \text{ GeV/c for the positive tracks,}$$

and

$$\overline{P}_T = 0.397 \text{ GeV/c for the negative ones.}$$

On the contrary, the distribution of the longitudinal momentum P_L^* (Fig. 2) shows a big difference between positive and negative tracks, the first being preferentially emitted backward and the second being emitted forward.

The P_T^* values are in agreement with the ones already observed by other authors in the study of high-energy collisions, produced by cosmic rays ([8])

([8]) E. Lohrmann, M. W. Teucher and M. Schein: *Phys. Rev.*, **122**, 672 (1961).

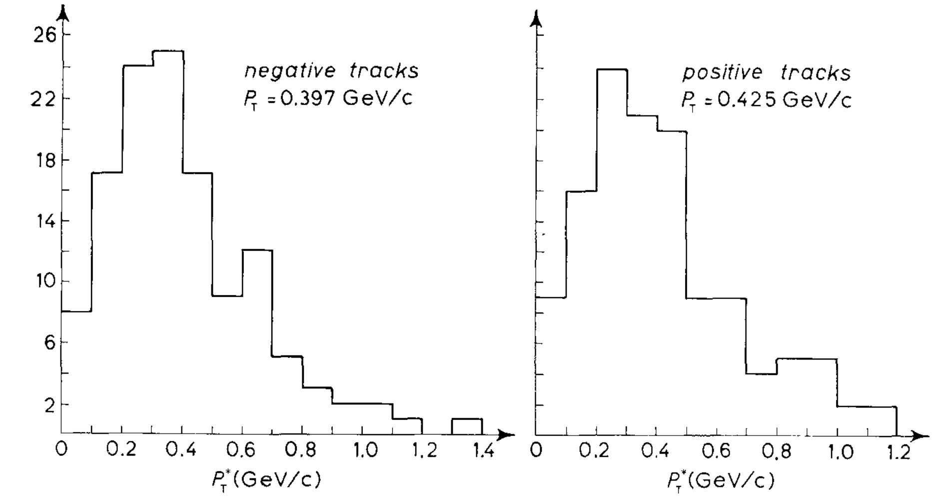

Fig. 1.

or by particles artificially accelerated (9). The behaviour of P^*_T and P^*_L distributions clearly means anisotropy in the centre of mass angular distributions, and also asymmetry if one considers separately the positive and negative

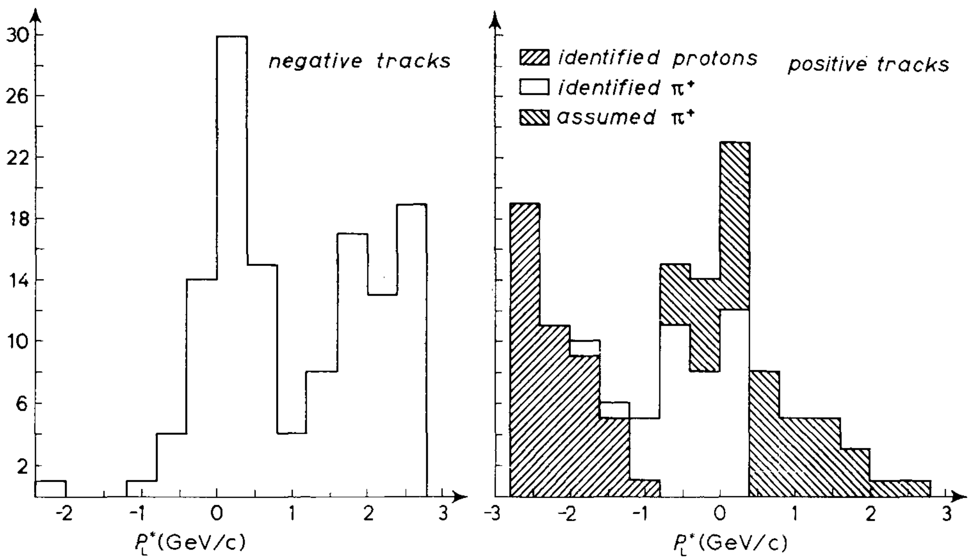

Fig. 2.

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(9) W. P. Dodd, H. Jobes, J. B. Kinson, B. Tallini, B. R. French, W. Neale, S. Norbury and D. Radojicic: *Aix-en-Provence International Conference on Elementary Particles*, Vol. **1** (1961), p. 433.

tracks. This was already observed for low multiplicity jets in the study of collisions produced on hydrogen by π^--mesons of nearly the same energy as ours [9].

Another consideration to be viewed concerns the P_L^* distributions for negative particles: this distribution shows two groups of events quite well separated. One is characterized by the presence of a very fast π^--meson ($P_L^* > 1.2$ GeV/c) and has no correspondence in the P_L^* distribution for positive pions; the second one has a π^--meson with P_L^* distributed around the zero value and looks more similar to the P_L^* distribution of π^+-mesons, even if these latter are slightly more backwards. The same behaviour was observed by MORRISON [1] who found, however, that the separation between the two groups occurs at $P_L^* \sim 1.4$ GeV/c; the difference is probably due only to uncertainty in the measurements.

In what follows we shall consider these groups of events separately.

5. – Events with a fast π^--meson.

The correlation of the P_L^* of the positive and of the negative track is shown in Fig. 3, for each event; different symbols are used to take into account the presence of π^0-mesons. If one looks at the group of events with a π^--meson of $P_L^* > 1.2$ GeV/c, one can see that, on a total of 57 cases, there are:

— 18 cases in which the positive particle is recognized to be a proton (reactions (1) and (2) of Section **1**);

— 39 cases in which the positive particle is recognized (24 cases), or assumed (15 cases) to be a π^+ (reactions (3) and (4) of Section **1**).

In order to distinguish between reactions (1) and (2) and between reactions (3) and (4), one has to consider the π^0 production. The presence of a π^0-meson is indicated by the observation of one γ-ray; when two γ's are observed, one can kinematically decide if they are produced by the same π^0-meson: in this case we say that we observe one π^0. A first selection has been made dividing conventionally the observed events in the following way:

reaction (1): no γ, or one γ or one π^0;

reaction (2): 2 γ's, or 1 γ and 1 π^0, or 2 π^0;

reaction (3): no γ;

reaction (4): one γ or one π^0.

This attribution would be the correct one in the case in which all γ's produced will be observed. We have however to take into account the corrections due to the fact that the probability of observing a γ-ray in the chamber is not one. A first cause of correction might come from events with more than 3 final pions which could be attributed to any of these four reactions. However we point out that the sample of 57 events considered in this section is very likely to be clean from such a contamination; indeed out of the 32 cases rejected because of pion multiplicity > 3 (see Section **3**), only 1 was in the group of events with $P_L^* > 1.2$ GeV/c for the π^0-meson.

A second cause of correction comes from the fact that some of the events attributed to reactions (1) and (3) in the first selection, actually are due to reactions (2) and (4) respectively. So, the numbers obtained in the first selection (second column of Table I) have been modified taking into account the probability of observation of γ-rays in our chamber (see Section **2**), obtaining the « corrected numbers » that appear in the last column of Table I.

TABLE I.

Type of reaction	Observed numbers	Corrected numbers
1) $\pi^- + p \to \pi^- + p + \pi^0$	16	13
2) $\quad\quad \to \pi^- + p + \pi^0 + \pi^0$	2	5
3) $\quad\quad \to \pi^- + n + \pi^+$	29	24
4) $\quad\quad \to \pi^- + n + \pi^+ + \pi^0$	10	15

Those figures are of course affected by statistical uncertainties, and have to be considered only as an indication.

The corrected figures in Table I might be used to give a rough evaluation of the cross-sections for the emission of a fast π^--meson through reactions (1), (2), (3) and (4). Taking into account the beam contamination and the percentage of glancing collisions on bound protons, the cross-section for collision on free protons turns out to be, as order of magnitude:

$$\sigma_{(1)+(3)} \approx 1 \text{ mb} , \qquad \sigma_{(1)+(2)+(3)+(4)} \approx 1.5 \text{ mb} .$$

The cross-section obtained by MORRISON [1] for the same type of events produced by π^- of 16 GeV/c, with a lower statistics and without selection on the number of π^0 emitted is 2.25 mb.

We wish to outline here that from our experimental results the contribution of reaction (3) is twice the contribution of reaction (1). It seems moreover that, also if we add the contribution of reactions (2) and (4), the target proton has always double probability of being emitted as a neutron rather than as a proton. This confirms Morrison's [1] results, which give the same ratio of 2 between emitted neutrons and protons without selection on the number of π^0 emitted.

6. – Events with a slow π^--meson.

At first sight, looking at Fig. 3, one recognizes that in the group of events with a π^--meson of $P_L^* > 1.2$ GeV/c the contribution of cases in which three

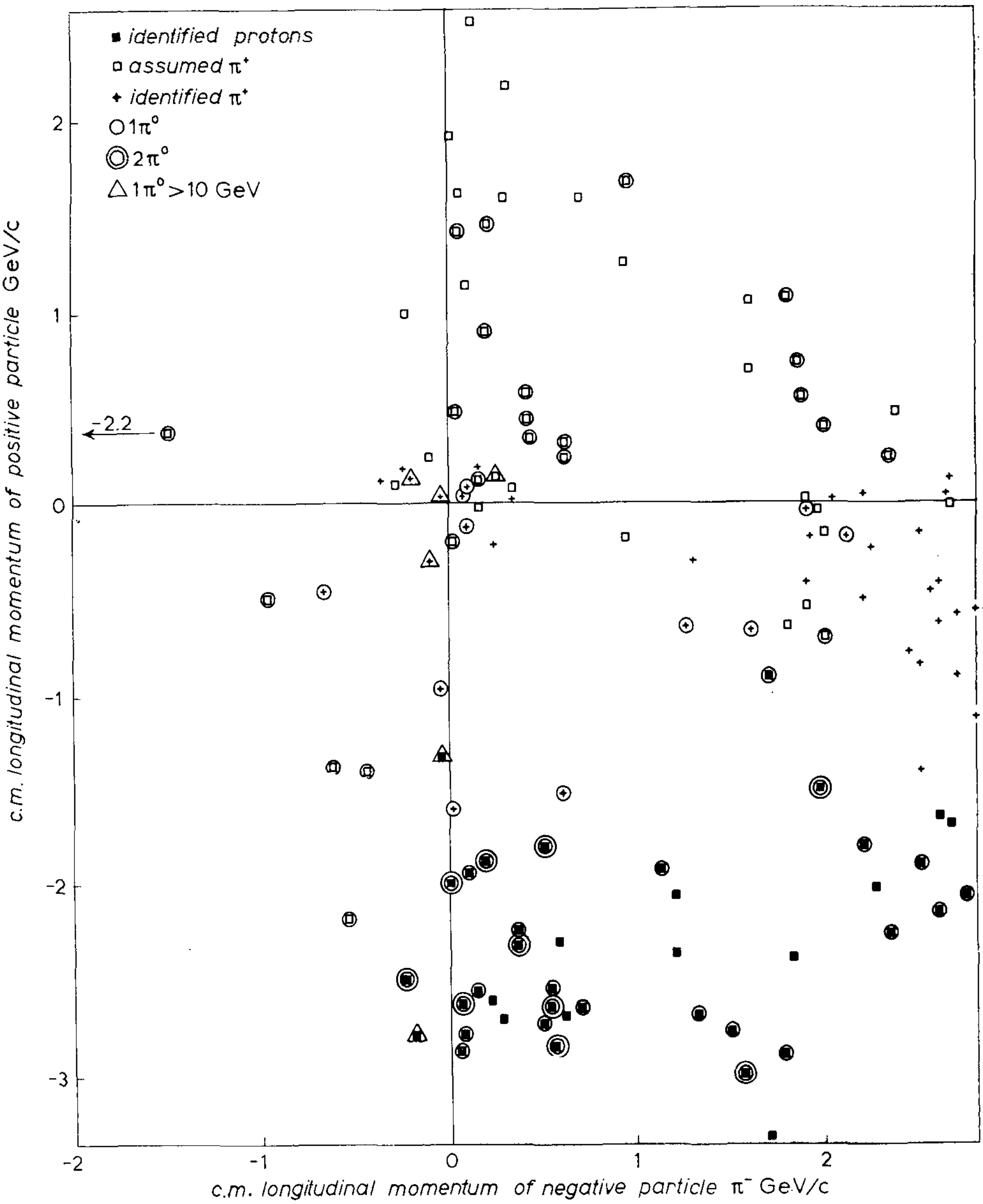

Fig. 3.

pions are emitted is much bigger. Furthermore one has to remember that the 32 cases rejected because their pion multiplicity was >3 were in the energy region of the π^--meson; so that it is not so straightforward to find a simple interpretation of this group of events.

We shall try, however, to discuss their most important features. First of all, let us divide them as we did for the events of Table I, according to the four reactions studied in this work:

TABLE II.

Type of reaction	Observed numbers	Corrected numbers
1) $\pi^-+p\to\pi^-+p+\pi^0$	15	3
2) $\to\pi^-+p+\pi^0+\pi^0$	8	20
3) $\to\pi^-+n+\pi^+$	19	5
4) $\to\pi^-+n+\pi^++\pi^0$	27	41

This table is affected by a bigger uncertainty than Table I, because of the unknown contamination of events with more than three pions emitted. What we can learn from this Table II is only that, as it is easy to understand, almost all the events belong to reactions of type (2) and (4). In fact, the existence of reactions (1) and (3) when both the π^--meson and the barion are slow, would mean the emission of a very fast π^0 or π^+-meson; if no one of these fast mesons would have been observed, one had to conclude that reactions (1) and (3) are present in nonnegligible percentage only when a fast π^- is emitted. This conclusion would not be in disagreement with the experimental results: in fact the number of events of the kind (1) and (3) (which in Table II is given by 3 and 5), can easily be considered as zero, due to the uncertainties explained at the beginning of this section.

The point is that, as it appears in Fig. 3, between the 15 events attributed as « observed numbers » to reaction (1) there are two cases with a π^0-meson emitted with more than half of the incident energy, and between the 19 events attributed as « observed numbers » to reaction (3) there are six cases with a π^+-meson emitted with more than half of the incident energy.

Furthermore there are 4 cases of a very fast π^0-meson emitted in reactions of the kind (4), and 3 cases of a very fast π^+-meson emitted in reactions of the kind (3).

These few cases are then characterized by the emission of a very fast particle that has nearly the same momentum and direction of the incident particle but different charge.

7. – Experimental conclusions.

The most striking feature of our results is that, in a great percentage of the analysed events, one of the emitted π-mesons comes out with almost all the incident energy. Generally, such a π-meson is negative, *i.e.* of the same charge as the incident one; however in a nonnegligible part of the cases, the most energetic π-meson has a different charge. In fact, among all the analysed events, we have observed:

— 2 cases with a fast π^0-meson, attributed to reaction (1);

— 6 cases with a fast π^+-meson, attributed to reaction (3).

If one believes that these cases are actually due to reactions (1) and (3), these numbers have to be compared with the 37 events with a fast π^--meson attributed to the same reactions (1) and (3); consequently the percentage of events with the charge of the fast emitted meson different from the incident charge is $\sim \frac{8}{37} \sim 20\%$. If one considers that all the four reactions contribute to the emission of fast π^0 or π^+-mesons, as it is suggested by the observation of:

— 4 cases with a fast π^0-meson, attributed to reaction (4);

— 3 cases with a fast π^+-meson, attributed to reaction (3);

the percentage given above becomes $\sim \frac{15}{57} \sim 26\%$ (where 57 is the total number of events in which a fast π^--meson is emitted).

8. – Theoretical discussion.

The events studied in this work show the following main features:

a) small transverse momenta ($\overline{P}_T$ of the order of 0.4 GeV/c);

b) final nucleon slow in the laboratory system, *i.e.* emitted with large backward momentum in the c.m. system;

c) one final pion very fast (it takes more than half of the incident energy) which is a π^- in the largest number of cases.

We concentrate the theoretical discussion on the events with 3 outgoing particles (reactions (1) and (3)); the case of more particles emitted can be carried out in an analogous way.

From features *a*) and *b*) one can interpret those events as due to a collision of the incident pion on the peripheral meson of the nucleon (see Fig. 4).

On the other hand, the features *a*) and *b*) show that the collision of the incident pion on the peripheral pion is a strongly anisotropic one. Therefore such a scattering can be interpreted as a diffraction scattering, and this interpretation is confirmed by the fact that the fast pion has the same charge of the incoming one in almost all the cases. This model of a diffraction scattering on the peripheral pion has been proposed by DRELL and HIIDA ([3]).

The diffraction scattering is at present interpreted ([10]) (on the basis of the theory of the Regge poles) as due to the exchange of the so-called « vacuum pole » with $T=0$. In this case, the diagram of Fig. 4 can be written, in a schematic way as:

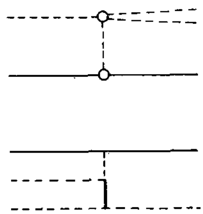

Fig. 4.

The fact that there is a ratio of the order of 2 between the number of cases in which the emitted nucleon is a neutron (reaction (3)) and the number of cases in which the emitted nucleon is a proton (reaction (1)), is easily interpreted on the basis of this model. In fact this ratio will be given by a factor 2 (due to the pion-nucleon vertex) multiplied by $\sigma(\pi^-\pi^0)/\sigma(\pi^-\pi^+)$ (where σ is the elastic cross-section). The ratio of elastic cross-sections $(\pi^-\pi^0)$ and $(\pi^-\pi^+)$ is theoretically equal to 1, due to the $T=0$ of the exchanged vacuum pole.

It is important to note that some exceptional cases have been observed, in which the final fast particle ($E_{\text{lab}} > 10$ GeV) has neutral or positive charge. This fact represents an example of a rare effect of great theoretical importance: the diffraction phenomenon in which the incident particle undergoes a change in a quantum number. This « charge-exchange diffraction » is of very difficult interpretation by means of classical models, but comes out of the Regge poles theory as a consequence of the exchange of a pole having quantum numbers different from the ones of the vacuum.

For example, when the fast particle is identified as a π^0-meson (2 cases in reactions with three final particles and 4 cases in reactions with four final particles) the phenomenon is due the exchange of the ϱ pole ($T=1$) which is responsible for the elastic scattering $(\mathcal{N}\mathcal{N})$ $(\pi\mathcal{N})$ $(\pi\pi)$ with charge exchange. It is interesting to remark that the effect of such a pole on the first two types of scattering $(\mathcal{N}\mathcal{N})$ and $(\pi\mathcal{N})$ is extremely small, probably because of the small

([10]) For a thorough discussion of experimental implications of Regge poles in high-energy scattering see Drell's report at the *11-th International High-Energy Physics Conference at CERN* (1962).

coupling ($\varrho\mathcal{N}\mathcal{N}$). Here on the contrary it seems to be a nonnegligible effect.

As to the positive fast particles, they can be interpreted as π^+-mesons or as protons. In the first case, (which seems to be the most reasonable interpretation) this is an indication for the existence of a new trajectory with $T=2$. In the second case, the trajectory would have baryonic number equal to 1. We have observed a total of 9 cases of positive particles emitted with more than half of the incident energy (6 cases in reactions with three final particles and 3 cases in reactions with four final particles). In addition 5 cases of fast positive particles emitted in π^--p interactions have been found previously by MORRISON [1] (no π^0 production could be observed by MORRISON due to experimental limitations).

In conclusion, our experimental results, although of a very preliminary nature, are an indication in favour of the theoretical picture of high-energy collisions based on peripheral models and Regge poles.

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We thank Prof. LAGARRIGUE for giving us the possibility of working on the film of the Ecole Polytechnique propane bubble chamber.

We are greatly indebted to Prof. S. FUBINI for many useful discussions and criticism, especially concerning the theoretical meaning of our results.

RIASSUNTO

Questo lavoro riguarda lo studio delle interazioni di mesoni π^- di 18 GeV/c nelle quali sono prodotti al massimo due pioni. I risultati confermano che, per questi eventi, lo scambio di un solo pione è il processo dominante. Viene inoltre suggerita una possibile interpretazione della struttura del vertice pione-pione.