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A STUDY OF DIRECT AND INDIRECT PION PRODUCTION

IN π^+ p INTERACTIONS AT 16 GeV/c

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ABSTRACT

The sources of negative pions are analysed in π^+p interactions at 16 GeV/c. It is shown that the kinematics of resonance decay is crucial in determining the pions' longitudinal and transverse momentum spectra. The identifiable meson resonances, of which η, ω, ρ^0 and f are the dominant ones, account for about 50% of all π^- 's produced. The "direct" pions, i.e. those that are primary products of the π^+p interactions, appear to constitute 10 to 30% of the total π^- yield.

1. INTRODUCTION

It has recently been emphasized [1-3] that there are two distinct sources for pion production in high-energy hadronic interactions, namely the "direct" and the "indirect" mechanism. In the direct mechanism, pions appear as primary products of the hadronic interaction, while indirect pions are produced through the decays of resonances, i.e., through a two-(or more) step process. The distinction between direct and indirect pion production is implicit in quark-model calculations which have been made to predict the relative yields of different hadrons in high-energy collisions [1,2]. Moreover, the two-mechanism concept has proved valuable in the interpretation of the experimental transverse momentum spectra of π , η , ω , ρ^0 and f mesons [3-5].

Present theoretical [1,2] and experimental [3,6] indications are that the dominant source of pions is the indirect mechanism. In this paper we shall investigate the spectrum of pions produced indirectly by the decays of identifiable resonances, focusing our attention on the particular reaction

$$\pi^+ p \rightarrow \pi^- + \text{anything} \quad (1)$$

at 16 GeV/c incident momentum. We have chosen to study the π^- to avoid the complications resulting from leading particle effects. The results are based on a sample of 407 000 inelastic events from a bubble chamber experiment at the CERN PS. Of the total inclusive π^- cross section, about 50% can be accounted for by the decays of the heavier mesons (sect. 2). It is demonstrated that the decay kinematics exerts a strong influence on the pions' transverse momentum spectrum, and that different "source" resonances feed pions into different p_L and p_T regions depending on the Q -values of the resonance decays and on the number of decay products.

It should be mentioned that not only pions, but also heavier hadrons may be produced indirectly by the decays of still heavier objects. It is, however, unlikely that indirect production is important in governing the production of mesons heavier than pions at the energy considered here. For example, the transverse momentum spectra of the heavier mesons are

found to be similar to one another [3], without the excess at low p_T which is characteristic of indirect production. For this reason we shall not discuss here the indirect production of mesons other than pions. An important experimental difficulty concerns pions produced by the decays of heavy baryon resonances, which, in comparison with the mesons, have poorly-known cross sections and are difficult to identify.

After presenting in sects 4 and 5 the longitudinal and transverse distributions for indirect pions from various sources, we discuss in sect. 6 the problem of direct pion production. The conclusions of the paper are summarized in sect. 7.

2. SOURCES OF INDIRECT PIONS

Table 1 is a list of meson resonances [4,5,7-10] which contribute, by their decays, to the production of indirect π^- 's in reaction (1). Many heavier mesons are missing from the table, for the reason that no information about their (inclusive) production cross section is available. Allowances have been made to avoid double counting in the case of cascade-type decays (e.g. the η' contribution does not include that previously counted under the η in the decay $\eta' \rightarrow \pi\pi\eta \rightarrow 5\pi$). Note that π^- 's from A_1^+ and A_2^+ production are already counted under the ρ^0 ; a negative correction is made to allow for the resulting over-estimate of π^- 's when two overlapping ρ^0 's are produced with a single π^- in common. It is evident from table 1 that the ρ and the ω are the dominant mesonic sources of indirect pions. Smaller contributions come from the η , the f and the $K^*(890)$. All other meson resonances listed in table 1 contribute very little.

Baryon resonances are not included in table 1. This is because such resonances have not been well studied in production experiments, and very scanty information is available concerning their cross sections. By choosing to investigate π^- production here, the importance of baryon

resonances is reduced, because local charge conservation strongly favours resonances such as N^{*+} 's and $\Delta^{++}(1236)$ which yield few or no negative pions. The best-established baryonic source of π^- 's in reaction (1) is the diffractive dissociation $p \rightarrow (p\pi^+\pi^-)$, which could account for about 0.6 mb. It is clear that, if baryon resonances are to rival meson resonances as a π^- source in reaction (1), then there must exist N^* 's with substantial cross sections beyond those identified in production experiments. These heavy N^* 's could have avoided detection on account of their large number and large widths causing overlap, and also because of their multibody decay.

In summary, about 50% of the π^- 's production in reaction (1) comes from decays of known mesons, 44% being from the vector mesons ρ^0 and ω alone. Having studied negative pions produced in the interactions of positive pions with protons we have minimized the influence of the incident particles (leading particle effects) and it may therefore be expected that the results obtained will be qualitatively true for the high-energy collisions of any hadrons.

3. DIFFERENTIAL CROSS SECTIONS FOR PIONS FROM η , ω , ρ^0 AND f DECAYS: EXPERIMENTAL PROCEDURE

In this section and in sects 4 and 5, data will be presented on negative pions produced from the decays of η , ω , ρ^0 and f in reaction (1). The following final states are analysed:

$$\pi^+ p \rightarrow \eta + \text{charged particles} \quad (4)$$

$$\pi^+ p \rightarrow \omega + \text{charged particles.} \quad (5)$$

That is to say, the ρ^0 and f are studied inclusively (the latter only in its $\pi^+ \pi^-$ decay mode) and the η and ω are studied quasi-inclusively, i.e. in reactions where they are accompanied only by charged particles. This is necessary in order for the π^0 in the η or ω decays to be kinematically fitted. Note that here the $\pi^+ \pi^- \gamma$ decay of the η is not distinguished from the $\pi^+ \pi^- \pi^0$ decay mode.

The method employed to obtain the differential cross sections for the decay pions is the same as was used in ref. [11] to study kaons from decays of K^* (890), and may be illustrated by an example: Suppose the rapidity (y^*) distribution is to be obtained for π^- 's from ρ^0 decays, to be noted by $\pi_{\rho^0}^-$. The effective mass spectrum of the $\pi^+ \pi^-$ combinations is first plotted for each chosen interval (bin) in the rapidity of the π^- . Each spectrum is then fitted to give the corresponding ρ^0 cross section, which is the same as the $\pi_{\rho^0}^-$ cross section in that y^* bin. With this procedure, the differential cross sections are found in a consistent manner over the whole phase space, the background subtraction being carried out by fitting mass spectra. So there is no need to assume that the differential distribution of the background under the resonance signal is the same as that of the signal or the neighbouring regions. Details of the resonance fitting have been presented elsewhere [4,5].

The inclusive cross sections for π_{η}^- and π_{ω}^- are estimated by scaling up the quasi-inclusive cross sections (reactions (4) and (5) above). This is justified by the argument [4] that the η and ω distributions for the quasi-inclusive reactions are likely to be similar to the corresponding fully-inclusive distributions.

4. LONGITUDINAL DISTRIBUTIONS OF PIONS FROM η , ω , ρ^0 AND f DECAYS

Following the procedure outlined in the previous section, differential cross sections have been obtained in terms of the c.m. rapidity (y^*) and Feynman variable (x) for the negative pions produced in reaction (1) as decay products of η , ω , ρ^0 and f mesons. They are presented in figs 1 and 2, together with the inclusive distributions for all π^- 's. In fig. 1 all the distributions are asymmetric, with more pions in the forward hemisphere than backward. This is to be expected in view of the presence of a baryon which will generally have large momentum in the backward direction, then the majority of the mesons will move forward so as to conserve momentum. This feature is more strikingly shown in fig. 2, where the invariant cross section of negative pions is given as a function of $x = p_L^*/p_{\max}^*$, where $p_{\max}^*$ is the maximum possible momentum of the π^- in the c.m. system. The distributions for π_{η}^- and π_{ω}^- are similar to each other and clearly narrower than those for $\pi_{\rho^0}^-$ and π_f^- (the distribution for π_f^- is almost flat in the region $x > 0$). This is mainly due to different decay kinematics: $\pi_{\rho^0}^-$ and π_f^- derive from two-body decays with relatively high Q-values, whereas π_{η}^- and π_{ω}^- come from three-body decays with much smaller Q-values (the productions of the "parents" η and ω , and of the ρ^0 itself, are known to have similar x -dependence [5]).

Overall, the indirect negative pions from η , ω , ρ^0 and f decay shown in fig. 1 account for about 40% of the total π^- inclusive cross section, but if we consider only the faster half of the π^- 's (those with rapidity above the median at $y^* \approx 0.25$) this fraction rises to 50%, while for the slower half of the π^- 's, only about 30% is accounted for by the mesonic resonances considered. More quantitative conclusions can be drawn from fig. 3, which shows the invariant cross section as a function of x , for all π^- 's, and for the π^- 's from η , ω , ρ^0 and f decays taken together. It is seen that in the region $x > 0.25$ appreciably more than 50% of the fully inclusive π^- cross section is accounted for by decay products of η , ω , ρ^0 and f mesons. Their contribution is smaller, being only about 25%, in the region $-0.4 < x < 0$.

5. TRANSVERSE MOMENTUM DISTRIBUTIONS OF π^- 's FROM η , ω , ρ^0 AND f DECAYS

Fig. 4 shows the distributions of the squared transverse momentum, p_T^2 , for the η , ω , ρ^0 and f mesons and for the negative pions produced by their decay, in reactions (2) to (5). It can be seen that to a first approximation all spectra fall like exponentials in p_T^2 . The average values of p_T^2 and of p_T are collected in table 2, and they show that the spectra for the four meson resonances are rather similar to one another, with an average p_T of around 470 MeV/c. Their decay products, however, have very different transverse momentum distributions, with the average transverse momentum increasing substantially as one goes from the η meson, close to the three-pion threshold, up to the f meson at high mass. As a rule, the pions are produced at lower p_T values than the parent resonances; only for the f meson do we find that the large kinetic energy released in the decay allows the "daughter" pions to appear with average p_T as large as that of the f itself.

In fig. 5, the p_T^2 distributions of the negative daughter pions are shown together with the total inclusive π^- spectrum. It is evident that the characteristic shape of the inclusive π^- spectrum, with a sharp peak at low p_T , must be largely due to the way in which it is built up from the distributions of decay pions.

Fig. 6 shows how the percentages of the total inclusive π^- cross section contributed by the η , ω , ρ^0 and f decays varies with the π^- transverse momentum. At very low p_T , the ω is the main single source of negative pions, accounting for about 20% of the total. At $p_T^2 \approx 0.5 \text{ (GeV/c)}^2$, ρ^0 becomes predominant, producing about 30%, while the ω contribution is down to only a few percents. As p_T increases further, the importance of ρ^0 slowly decreases and a substantial fraction of the π^- 's begins to be produced by the f .

It is thus evident that the detailed kinematics of the sources of indirect pions plays an important part in determining the shape of the spectrum of inclusive pions. In this light, it seems remarkable that the transverse spectra of pions have in the past been satisfactorily described in thermodynamical terms [12] without explicitly considering resonances.

6. PIONS PRODUCED OTHER THAN BY η , ω , ρ AND f

As shown in table 1, about 40% of the negative pions produced in π^+p interactions at 16 GeV/c are decay products of the η , ω , ρ^0 and f mesons and this percentage increases to 49% when the contribution of the ρ^- is added, while very little is contributed by the other mesons listed in table 1. Let us denote by $\pi_{\eta\omega\rho f}^-$ the negative pions deriving from η , ω , ρ^0 , ρ^- and f decays. The remaining π^- 's must be produced either directly (π_{dir}^-) or indirectly as decay products of baryon resonances (π_B^-) and of meson resonances other than η , ω , ρ and f , (π_M^-). The question of how many the direct pions are, is not an easy one to answer. Some insight may be gained, however, from the longitudinal and transverse distributions presented in sects 4 and 5.

That baryonic resonances must play an important role in supplying negative pions is indicated by the x distributions in fig. 3, which shows that while in the forward region η , ρ^0 , ω and f account for more than 50% of the total π^- yield, only $\sim 25\%$ of it is contributed by them in the backward direction, where baryons are expected to be.

Further insight may be gained from comparing the traverse spectrum of all π^- 's (π_{incl}^-) with the p_T -spectrum obtained by summing the contributions of the dominant meson resonances, η , ω , ρ^0 , ρ^- and f ($\pi_{\eta\omega\rho f}^-$). This is done in fig. 7, where these two spectra and their difference are shown. Note that here the contribution of ρ^- is added with the assumption that it has the same p_T distribution as that from ρ^0 (*).

It is interesting to see that while η , ω , ρ and f individually feed π^- 's in very different p_T ranges, the sum of their contributions happens to be a more or less constant fraction of the total yield ($\sim 50\%$) over all p_T -values. Consequently, also $\pi_{\text{difference}}^-$ has a p_T -spectrum that

(*) Studied quasi-inclusively (using reactions in which ρ^- is accompanied only by charged particles), π_{ρ^-} was found to have a p_T^2 distribution similar in shape to that of π_{ρ^0} .

roughly parallels the inclusive spectrum. Again, this must be understood in terms of superposition of different p_T spectra of the various component contributing to π^- difference, i.e. π_{dir}^- , π_B^- and π_M^- .

The π_{dir}^- component may be expected to have a relatively large average p_T , with a spectrum rather like those of the heavier mesons which appear in fig. 4 and ref. [3]. The π_B^- spectrum, on the other hand, is likely to be much more sharply peaked towards zero transverse momentum, since a baryon resonance will have a baryon among its decay products which on average must take up the greater part of the resonances transverse momentum. A quantitative example will make this clear: for the 16 GeV/c π^+p data analysed here, the maximum c.m. momentum is about 2.7 GeV/c and this is therefore the greatest possible transverse momentum that may occur. If an N^* resonance is produced with this p_T value and subsequently decays into a nucleon and a pion, then the transverse momentum will be shared by the decay products in proportion to their masses (for an N^* not too far above threshold)^(*). So, the π_B^- spectrum must be strongly curtailed by phase space for p_T above a few hundred MeV/c.

For the reasons outlined above, it may be expected that the π_B^- component will be insignificant at the highest p_T values accessible to us. In fact, only the ρ and the f mesons appear to be important sources of pions above $p_T = 1$ GeV/c (provided that other mesons having two-body decays with high Q-value, e.g. the ϵ , have cross sections small compared to those of the ρ and f). It may then be concluded that for such p_T values, no more than about 50% of the π^- 's are indirectly produced, that is to say $\pi_{\text{dir}}^-/\pi_{\text{incl}}^- \approx 0.5$. Thus, it is likely that at the highest p_T values shown in fig. 7 the difference spectrum $\pi_{\text{incl}}^- - \pi_{\eta\omega\rho f}^-$ reflects the production of direct pions π_{dir}^- . At low p_T values, the situation is much less clear: the fraction of pions from baryon resonances π_B^- is not known

(*) It has been verified experimentally that in π^+p interactions [13] at 16 GeV/c practically all pions from decays of $\Delta^{++}(1236)$ have p_T^2 values less than 0.2 (GeV/c)^2 .

and there can be some contribution from less well-known meson resonances (with any type of decays) as well. It is not clear, either, how π_{dir}^- should be extrapolated from the high to the low p_T region. In ref. [3] it has been pointed out that the transverse spectra $d\sigma/dp_T^2$ of η , ω , ρ^0 and other mesons, produced in a number of different experiments, are all approximately exponential, with remarkably similar slopes, $\approx 3.4 \text{ (GeV/c)}^{-2}$. Assuming that (i) π_{dir}^- has similar p_T distribution in shape as these mesons which are heavier and that (ii) the ratio $\pi_{\text{dir}}^-/\pi_{\text{incl}}^- = 0.5$ at $p_T^2 \approx 2 \text{ (GeV/c)}^2$, an estimate

$$\pi_{\text{dir}}^-/\pi_{\text{incl}}^- = 10\% \quad (6)$$

is obtained for the fully inclusive case.

For the reasons discussed in detail in ref. [3], the value of 10% should be considered to be a lower limit, rather than a final estimate, for the fraction $\pi_{\text{dir}}^-/\pi_{\text{incl}}^-$. On the other hand, well-known meson decays alone account for half of all π^- 's (table 1). To allow some π^- 's to be produced via less known meson and baryon decays, a realistic estimate would be

$$\pi_{\text{dir}}^-/\pi_{\text{incl}}^- \lesssim 30\%. \quad (7)$$

In conclusion, the ratio $\pi_{\text{dir}}^-/\pi_{\text{incl}}^-$ is likely to lie between 0.1 and 0.3.

Eqs (6) and (7) mean that the majority of pions are indirectly produced by resonance decay, and therefore their spectrum is built up in a complicated way.

7. CONCLUSIONS

Of all the negative pions produced in 16 GeV/c π^+p interactions, about 49% originate from the decays of the mesons η , ω , ρ and f . Their p_T spectrum is strongly dependent on the kinematics of these decays and different p_T regions contain pions of very different origins. Similar conclusions can be drawn for the longitudinal distributions.

Of the remaining π^- yield, a few percents may come from the decays of other assorted mesons while a larger fraction must derive from baryon resonance decays. The direct production of pions which are not resonance decay products is estimated to be somewhere between 10% and 30%.

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TABLE CAPTIONS

Table 1 Cross sections for mesons produced in π^+p interactions at 16 GeV/c.

Table 2 Average squared transverse momentum $\langle p_T^2 \rangle$ and average transverse momentum $\langle p_T \rangle$ for mesons produced in π^+p interactions at 16 GeV/c.

TABLE 1

Parent meson	$\sigma(\text{parent})$ (mb)	Contribution to $\sigma(\pi^-)$ (mb)	Reference or assumption
ρ^0	4.8 ± 0.4	4.8 ± 0.4	[4]
ρ^-	2.3 ± 0.5	2.3 ± 0.5	[7]
f	0.99 ± 0.10	0.63 ± 0.07	[4]
ω	4.0 ± 0.7	3.7 ± 0.6	[5]
η	1.5 ± 0.3	0.44 ± 0.09	[5]
η'	~ 0.1	~ 0.07	$\eta'/\eta = 0.75$ [5]
ϕ	~ 0.1	~ 0.01	From $\pi^- p$ expt [8]
g^0	0.32 ± 0.20	$0.08 \pm 0.05^{(a)}$	[9]
K_{890}^{*-}	0.18 ± 0.05	0.12 ± 0.03	[10]
K_{890}^{*0}	0.71 ± 0.10	0.47 ± 0.07	$K^{*0} = K^{*+}$ [10]
A_1^+, A_2^+		-0.23	Correction for ρ^0 double counting
TOTAL		$12.4 \pm 0.9 \text{ mb} = (51\% \pm 4\%) \sigma_{\text{tot}}(\pi^-)$	

(a) Includes the 2π decay mode only.

TABLE 2

Particle	$\langle p_T \rangle$ (GeV/c)	$\langle p_T^2 \rangle$ (GeV/c) ²
η	0.51 ± 0.02	0.31 ± 0.02
ω	0.47 ± 0.02	0.29 ± 0.02
ρ^0	0.46 ± 0.01	0.27 ± 0.01
f	0.43 ± 0.02	0.25 ± 0.02
π^-_{η}	0.20 ± 0.01	0.055 ± 0.005
π^-_{ω}	0.24 ± 0.01	0.075 ± 0.004
$\pi^-_{\rho^0}$	0.38 ± 0.01	0.18 ± 0.01
π^-_f	0.48 ± 0.02	0.29 ± 0.02
π^-_{all}	0.31 ± 0.01	0.14 ± 0.01

FIGURE CAPTIONS

- Fig. 1 c.m. rapidity distributions of inclusive π^- and of π^- 's from various parent resonances. The arrows correspond to the minimum and maximum values of $y^*(\pi^-)$.
- Fig. 2 Invariant distribution in x of inclusive π^- and of π^- 's from η , ω , ρ^0 and f decays. The curves drawn are merely to guide the eye.
- Fig. 3 Invariant distribution in x of inclusive π^- and of the sum of π^- from η , ω , ρ^0 and f and the difference of these two. The curves drawn are merely to guide the eye.
- Fig. 4 p_T^2 distributions for: (a) η and π^-_η , (b) ω and π^-_ω , (c) ρ^0 and $\pi^-_{\rho^0}$ and (d) f and π^-_f .
- Fig. 5 p_T^2 distributions for inclusive π^- , $\pi^-_{\rho^0}$, π^-_f , π^-_η and π^-_ω . The curves drawn are merely to guide the eye.
- Fig. 6 p_T^2 dependence of ratio of π^- from η , ω , ρ^0 and f respectively to that of inclusive π^- . The curves drawn are merely to guide the eye.
- Fig. 7 p_T^2 distribution of inclusive π^- and of the sum of π^- from η , ω , ρ^0 and f and the difference of these two.

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Fig. 1

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Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

THE
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