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ANALYSIS OF INELASTIC PROTON-PROTON INTERACTIONS

IN THE 1 TO 10 GeV ENERGY RANGE

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ABSTRACT

Different experimental spectra relevant to inelastic proton-proton interactions, at incident energies between 1 and 10 GeV, are compared with the predictions of the one-pion exchange (OPE) model, by taking into account the production of one and two pions. This analysis gives a further confirmation of the validity of the OPE model below 3 GeV ; with increasing energy, it is found that the model deteriorates rapidly, and that other effects have to be taken into account. However the behaviour of the spectra at high energy seems to depend critically on the isospin of the exchanged system, and may be difficult to describe in terms of the pictures currently used for high energy inelastic interactions.

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I. OPE MODEL AND INELASTIC pp INTERACTIONS

Inelastic proton-proton collisions have always been of considerable interest for providing valuable information on the mechanism of nuclear interactions. The range of energy most widely investigated is between 1 and 10 GeV. At energies below 3 GeV the main inelastic contribution is given by single pion production ¹⁾; but already at 2 GeV double pion production shows up ²⁾, and at 3 GeV there is also a non-negligible contribution of triple and multiple pion production ³⁾. Above 3 GeV, the resolution of the various inelastic reactions becomes more and more difficult, but the importance of multiple pion production is obviously expected to increase.

Inelastic pp collisions in the 1 to 3 GeV energy range have been satisfactorily explained by the one-pion-exchange (OPE) model ⁴⁾, where "off-shell" corrections due to the virtuality of the exchanged pion have been introduced ^{5),6)}. This approach has been subsequently criticized by various authors ^{7),8)}, because it does not take into account the effects connected to the absorption of low partial waves in the initial and final states; such effects can play an important role in the description of the interaction, the more important the higher the energy ⁹⁾. Though some of the particular criticisms raised against the OPE approach can be questioned ¹⁰⁾, it is, however, apparent that the formulation of the OPE model applied in the region from 1 to 3 GeV is not expected to work at higher energies, and, should one try to use it altogether, quite sensitive discrepancies with the experiment must appear. It can, however, be of some interest to have a quantitative insight of the situation. With this purpose, and with the aim of a more complete understanding of the role of the OPE model in inelastic pp interactions, we are going to present a systematic comparison between such a theory and the experiment at various energies ranging from 1 to 10 GeV. We refer to a set of similar counter experiments performed by two experimental groups ^{11),12)}. The characteristic features of the experimental spectra have been widely discussed, but a detailed analysis of them so far does not exist in the literature: only some crude evaluations based on the OPE model can be found in the experimental papers.

The spectra to be discussed in this work are proton momentum lab. spectra at fixed lab. angles; i.e., doubly differential spectra. There is a remarkable difference between such spectra and those discussed in terms of the OPE model in Refs. ^{5),6)}; the latter are singly differential spectra, i.e., something like the result of an integration (over the energy or over the angle) of the distributions discussed in this paper. It is then clear that the comparison between theory and experiment under such conditions is more stringent than the former one ^{5),6)}, and allows to look at the suitability of the OPE model more closely.

By summarizing, we think that, from this analysis, it can be learnt what follows :

- i) a further test of the OPE model, under more stringent conditions, in the region where it seems to work (1-3 GeV); in particular, a check of the decrease of the assumed "form factors" with the momentum transfer;
- ii) a quantitative evaluation of the discrepancies, and then of the effects to be reproduced by a more realistic description of the phenomena, in the region of higher energies.

II. CHARACTERISTIC FEATURES OF THE EXPERIMENTAL AND OF THE CALCULATED SPECTRA

As we have already pointed out, all the spectra to be discussed in this paper are momentum distributions of the protons originated in inelastic proton-proton collisions and observed at a fixed angle in the lab. system. In such experiments it is not possible to discriminate the types of reactions where the observed particles have been produced. However, for all processes, once the scattering angle has been fixed, there is a one-to-one correspondence between the momentum of the observed proton and the invariant mass ω of the system of all the other particles emitted together with it ¹³⁾. Thus the energy spectrum can also be read as a "missing-mass"

spectrum. In this language, it is possible to speak of the "threshold" for a certain reaction; it is the value of the momentum above which the missing mass is less than the sum of the masses of the reaction products.

If the observed proton is produced together with an unstable particle (an "isobar"), a maximum should be observed at that value of the momentum which corresponds to the isobar mass (such a value obviously depends on the scattering angle). As is well known, final states of the type "nucleon+isobar" practically exhaust all the cases of single pion production. Therefore the maxima corresponding to the masses of the known nucleon isobars (we will call them N_{33}^* , N_{13}^* , N_{15}^* , N_{37}^*) ¹⁴⁾ should be quite pronounced in the experimental distributions, compatibly with phase space. Actually, such maxima are generally observed, and are clearly superimposed to a background starting at the threshold for double pion production. The OPE model accounts for the presence of such maxima quite naturally, like any other mechanism which explicitly considers the formation of resonant states.

When the observed proton is not produced alone together with an isobar ("direct proton"), but it comes out from the decay of the isobar ("recoil proton") or from a quasistatistical mechanism of multiparticle production, the features of its spectrum will not be so characteristic, and it will be difficult to predict the shape of the resulting distribution on general grounds. However, the OPE model allows to calculate the spectrum of the recoil proton in the simplest cases, which are also the most interesting (nucleon+isobar, isobar+isobar final states). Therefore in the present picture the background which is left uncalculated is strongly limited, especially at low energy, and its behaviour can be "checked" by reasonable criteria of plausibility.

In order to summarize, the experimental spectra will be compared with theoretical curves calculated according to the OPE model, and containing the following contributions :

4.

1. single pion production (i.e., nucleon+isobar final states, described by the diagram of Fig. 1), both for the direct and the recoil proton;
- 2a. double pion production, in the case of double isobar formation, described by the diagram of Fig. 2a;
- 2b. the (non-resonant) contribution to double pion production of the direct proton from the diagram of Fig. 2b (Drell diagram), which has been shown to be important for this process ⁶⁾.

Multiple pion production and the recoil proton from the Drell diagram will be assumed to contribute a statistical background (uncalculated) ¹⁵⁾.

We think the explicit calculation of double pion production to be quite significant in order to allow us to draw quantitative conclusions from this analysis. The fact that double pion production in pp collisions cannot be described only in terms of the OPE model ⁶⁾ should not be harmful here. In fact, the curves here obtained from the diagrams of Fig. 2 are quite smooth, and therefore they should not be strongly influenced by possible modifications of the OPE model, once the latter reproduces the gross features of all such reactions fairly well.

III. CALCULATION OF THE OPE SPECTRA AND COMPARISON WITH THE EXPERIMENT

The formulae used for the calculation of the OPE spectra are the standard ones already presented in FS, and do not need to be further explained. They have been easily generalized to the case of the double isobar diagrams (Fig. 2a). In the latter case, the simplifying assumptions used in Ref. ⁶⁾ have been dropped, and the calculation has been carried out in detail.

However, when dealing with a doubly differential spectrum, further difficulties arise with respect to the case of a singly differential spectrum: they will be discussed at this point.

First of all, it must be noted that the spectra of a recoil particle can be strongly influenced by the way how the isobar decays. A decay distribution peaked in the forward direction will generally increase the magnitude of the recoil spectrum at small lab. angles, and correspondingly depress it at large angles. Now, it happens that the decay distribution of a "pure" isobar, determined by its quantum numbers, can be modified by the interference with other small non-resonant partial waves; a priori, this modification can be different if the isobar is produced through an "off-shell" or an "on-shell" pion-nucleon collision. The attitude generally taken is to neglect such effects, and to consider the isobar always decaying as a pure state (e.g., the N_{33}^* decays like $1 + 3\cos^2\theta$). Nevertheless, this point brings a substantial uncertainty about the actual shape of the calculated spectra. In order to have an insight of what the possible changes of shape might be, we have calculated some of the spectra also under the assumption of an isotropic isobar decay, just as the simplest alternative to the pure-resonance hypothesis.

Another difficulty arises when the incident energy is so high that the observed recoil proton can be emitted by a system whose mass is larger than that of the third resonance (N_{15}^*). In this case a large non-resonant background is known to exist in pion-nucleon elastic scattering, both in the region of the fourth resonance (N_{37}^*) and above; this background comes mainly from diffraction scattering. Since the presence of a large diffractive contribution implies a strong peaking of the angular distribution in the forward direction, very large variations of the spectrum of the recoil proton can be obtained if this shape of the angular distribution is inserted in the calculation. In fact, a model of this kind had been proposed some years ago by Drell and Hiida¹⁶⁾, in order to explain the behaviour of the spectra of the type studied in this paper at an energy of about 16 GeV¹⁷⁾. At this energy, such spectra show no N_{33}^* formation, and have a maximum in the region of the two $T = \frac{1}{2}$ resonances; in the

Drell-Hiida picture, such a maximum was provided by the contribution of the recoil proton from a diffraction scattering in the four-particle vertex of Fig. 1. We have also taken this possibility into account, and looked at its implications at the lower energies. We have found that the introduction of diffraction in the OPE model always enhances the disagreement with experiment, and that the Drell-Hiida picture is also not adequate; the agreement obtained at 16 GeV seems to be accidental, and it is not maintained at the lower energies. In practice, for the description of the high-energy "tail" of pion-nucleon scattering, we have used a non-diffractive decay distribution, assumed to be uniform for simplicity; furthermore, we have neglected the contribution of the N_{37}^* resonance, according to the indications already existing at lower energies¹⁸⁾. This procedure is somewhat arbitrary, and will be further discussed later.

Let us now pass to the comparison of theory and experiment. Figures 3, 4, and 5 show the experimental data relevant to the energies below 3 GeV, as they are presented in Ref. ¹¹⁾, compared with the calculated predictions of the OPE model. The general agreement is quite satisfactory, especially at the two lowest energies. It is seen that anisotropic isobar decay is definitely more satisfactory than isotropic decay (as it had been already pointed out in Ref. ¹⁸⁾). The difference between the experimental and the calculated curves for momenta below the threshold for two-pion production is rather uniform in momentum and it is decreasing with increasing angle: the most straightforward explanation for it is that of a quasistatistical background due to more complicated production processes.

For a better understanding of this point, in Fig. 6 we have plotted the average value of such a "background" at the various energies as a function of the angle. At the lowest energy (1.3 GeV), where there is a very small amount of double and practically no multiple pion production, these points are not too significant, especially because of the fact that at this energy double pion production is very likely to be larger than the predictions of the OPE model¹⁹⁾. At the other two energies we have also plotted the average contribution of the Drell part of the spectra as a sort

of reference point : in fact, the actual background contains a contribution of this order of magnitude, plus the contribution of multiple pion production. The general behaviour of such a background seems to be consistent with the yield of multiple pion production, even though from a qualitative point of view only: in fact, it is awkward to infer any quantitative conclusions about a possible dependence on the energy or the momentum transfer.

More interest, on the other hand, can be found in the comparison of theory and experiment in the region of the N_{33}^* isobar. In this case, the momentum transfer Δ^2 to the observed proton is almost constant with the proton lab. momentum, whereas it is strongly varying with the scattering angle. Therefore, in this region, fixed-angle experiments are practically equivalent to fixed-momentum-transfer experiments. The Table gives the values of the average momentum transfer at fixed angle, for each of the spectra of Figs. 3, 4, and 5, both in the N_{33}^* region and in the off- N_{33}^* region. (Note that the latter values are less significant, because the averages are taken over a large interval of variation.) The agreement generally found for the decrease of the N_{33}^* peak with the scattering angle at all energies can be interpreted in terms of a "check" of the behaviour of the assumed form factors with the momentum transfer, up to a value of about $0.6 \text{ GeV}^2 \simeq 30 \mu^2$ (μ = pion mass). Only at the highest energy (2.85 GeV) the decrease of the isobar peak with increasing angle is experimentally faster than predicted: this can be interpreted as a first sign of deterioration of the theory, though on the whole, at this energy, the OPE model still gives a fairly good description of the phenomena.

This deterioration becomes more and more evident if we increase the incident energy. Fig. 7 shows the relevant spectra, as they are presented in Ref. ¹²⁾; in these measurements, the lab. scattering angle is always the same (60 milliradians), and the energy ranges from 3 GeV onwards. It should be pointed out that the comparison of the magnitudes of the theoretical and experimental curves is perhaps not too significant in this case, because the latter may be affected by an error of normalization ²⁰⁾ the only comparison of the shapes, however, gives a clear indication of the progressive deterioration of the model with increasing energy. In particular,

T_L (GeV)	1.35		2.05		2.85	
θ_L (degrees)	N_{33}^*	off N_{33}^*	N_{33}^*	off N_{33}^*	N_{33}^*	off N_{33}^*
2°	0.038	0.122	0.032	0.211	0.037	0.172
4°	0.045	0.181	0.054	0.238	0.086	0.210
8°	0.109	0.231	0.165	0.325	0.278	0.363
12°	0.196	0.300	0.323	0.444	0.535	0.682
17°	0.358	0.437	0.627	0.697	1.060	1.091

T A B L E

Values of the momentum transfer to the observed proton, Δ^2 , (in units of GeV^2), averaged over momentum at fixed scattering angle. Approximate values of the incident energies and scattering angles are indicated, in order to unify the notation: for the actual values, see Figs. 3, 4, and 5. The N_{33}^* region has been conventionally defined through the limitation $1.22 \leq \omega \leq 1.38$, in units of the proton mass.

the amount of N_{13}^* and N_{15}^* production brought in by the OPE model is definitely too poor in order to explain the huge humps experimentally observed. On the other hand, the rate of production of the isobar N_{33}^* is decreasing much more slowly in the OPE model than in the experiment. The different possible hypotheses on the behaviour of the high-energy "tail" of pion-nucleon scattering (presence or absence of N_{37}^* , diffraction, Drell-Hiida, etc.) cannot change the substantial disagreement between theory and experiment in this respect. Therefore, it does not seem to us to be a significant question to discuss the physical meaning of the approximations used in this calculation. The curves calculated under the

assumptions we have made (no diffraction, no N_{37}^*) have no stronger physical meaning than other possible curves calculated under different assumptions, but have mainly an indicative value, in the sense that they show a smaller discrepancy with the experiment. It has to be noted that such effects are not important at low energy, where the agreement between theory and experiment is good.

As far as the Drell-Hiida approach is concerned, it is anyway interesting to calculate the behaviour of this effect at the various energies (Fig. 8). It can be seen that the broad hump, falling in the region of the two $T=\frac{1}{2}$ resonances at 16 GeV, displaces towards the right with decreasing energy; such a trend is clearly not followed by the experiment. It should be noted that the curves of Fig. 8 are dependent on two somewhat arbitrary functions, i.e., the cut-off on the momentum transfer ("form factor") and the shape of the diffraction peak. For the curves calculated in this paper, we have not used the specific functions chosen by Drell and Hiida, but we have referred to the same functions used for the other spectra. However, we have seen that, by changing one or the other of such functions, the magnitude of the curves obtained is changed, but the position of the maximum remains always the same. Therefore the trend shown in Fig. 8 has a quite general character.

Finally, for the sake of completeness, in Fig. 9 we report two spectra of similar type, where protons from inelastic collisions are measured at large angles in the lab. system, in another experiment performed at 6.2 GeV²¹⁾. In these spectra, the momentum of the observed proton is kept fixed, and the angular distribution is directly converted into a distribution of the missing mass ω^2 . Apart from questions of scale, and from the large background which seems to be present, the unsuitability of the OPE model at this energy is quite evident. It should be noted that our theoretical curves look somewhat different from those calculated by the experimentalists in their paper, and also based on the OPE model; their interpretation of the influence of double-isobar formation on the shape of the spectrum is not confirmed.

IV. CONCLUDING REMARKS

As a conclusion, we have got the (perhaps expected) result that the OPE model with off-shell corrections is still a powerful tool of investigation of inelastic pp collisions at energies between 1 and 3 GeV, but that at higher energies it has to be replaced by a more realistic description. In particular, the latter must predict the most characteristic features of these spectra at high energy, i.e., the fast disappearance of the N_{33}^* isobar, and the enhancement of N_{13}^* and N_{15}^* production. The most intuitive explanation of this fact is that at high energy the dominating exchanged system has $T=0$, and all $T=1$ exchanges (including pion exchange) are overpowered by it. On the basis of this idea, Contogouris, Frautschi and How-sen Wong²²⁾ first tried an explanation by assuming the dominant system to be the Regge-pole Pomeranchuk trajectory.

Apart from this attractive explanation, it seems to be difficult to reproduce the experimental situation by starting from the proposed modifications of the OPE model based on the mechanism of absorption in the lowest partial waves⁸⁾, or on other similar approaches recently suggested^{23),24)}. The absorption effects are certainly present, and they will modify the predictions obtained in this paper: however, the marked isospin dependence which is experimentally observed seems to be difficult to obtain in terms of the present formulation of the above-mentioned models. It is possible that a more detailed formulation of such theories can give a good agreement with experiment.

It should be pointed out that the pp case is more difficult to treat than other cases (such as πp and Kp collisions), because of the presence of a large background below the resonant peaks. However, the attempt to describe also inelastic pp collisions in terms of a model valid for high energies might turn out to be extremely interesting. The fact that satisfactory, detailed predictions at low energy can be obtained from so simple a picture as the OPE model, may encourage one to pursue this kind of investigation.

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- 14) We use the notation N_{ij}^* for a nucleon isobar having isotopic spin $T = \frac{1}{2}i$ and spin $J = \frac{1}{2}j$. The fact that the spin assignments of the higher resonances have not yet been definitely assigned is not important in the present calculation.
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FIGURE CAPTIONS

- Figure 1. Typical diagram of single pion production in pp collisions through the OPE model. Full lines represent nucleons, wavy lines represent pions.
- Figure 2. Typical diagrams of double pion production in pp collisions through the OPE model : a) double isobar diagram, b) Drell diagram. Full lines represent nucleons, wavy lines represent pions.
- Figure 3. Experimental proton spectra in the lab. momentum P_L , at a fixed lab. angle θ_L (as presented in Ref. ¹¹), compared with the predictions of the OPE model. The incident kinetic energy T_L is of about 1.35 GeV. The theoretical contributions of single and double pion production are plotted separately ; their sum gives the total contribution. The influence of isotropic isobar decay (see text) is shown in one case. The experimental spectra here presented are taken from preliminary versions (more easy to be reproduced) of the published spectra : a consistency check has been made.
- Figure 4. The same spectra as in Fig. 3, at an incident kinetic energy of about 2.05 GeV.
- Figure 5. The same spectra as in Fig. 3, at an incident kinetic energy of about 2.85 GeV.
- Figure 6. The values of the resulting "background" $\bar{B}$ (i.e., the difference between the experimental and the theoretical points), averaged over momentum in the multiple pion production region, and plotted as a function of the scattering angle : a) at 1.35 GeV (taken from Fig. 3) ; b) at 2.05 GeV (taken from Fig. 4) ; c) at 2.85 GeV (taken from Fig. 5). In the two latter cases, the average values of the Drell contribution (Fig. 2b) are shown for comparison. The errors have been calculated on the basis of a rough estimate, and should be taken as indicative.

Figure 7. Experimental proton spectra in the lab. momentum P_L , at a fixed lab. angle θ_L , taken from Ref. ¹²⁾ and compared with the predictions of the OPE model. For the notation, see Fig. 3. The influence of diffraction in pion-nucleon scattering (see text) is shown at the two higher energies. Some experimental points with typical errors are also presented. The arrows indicate the positions of the nucleon isobars.

Figure 8. Plot of the contributions of the OPE diagram of Fig. 1, according to the picture of Drell and Hiida ¹⁶⁾, at $\theta_L = 60$ milliradians and different incident energies. In order to unify the notation, the momentum scale has been started at the position of the elastic peak. The arrows indicating the positions of the isobars are also shown.

Figure 9. Experimental spectra in the "missing mass" ω^2 at a fixed momentum P_L in the lab. system, taken from Ref. ²¹⁾ and compared with the predictions of the OPE model. For the notation, see Fig. 3 and the text. The arrows indicate the positions of the nucleon isobars.

FIG.1

a)

b)

FIG.2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

N_{33}^*

N_{13}^*
2.78
ALL OTHERS

N_{33}^*
2.78 5.82
ALL OTHERS

FIG. 8

FIG. 9