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QUARK MODEL AND ANNIHILATION AT HIGH ENERGY

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A B S T R A C T

Baryon-antibaryon annihilation contributions to high energy total cross-sections are discussed in the quark model. It is argued that they cannot be included in the additivity assumption for quark amplitudes. In this modified form, additivity with isospin and charge conjugation invariance predicts four relations, two of which are in very good agreement with the data while the other two are at present inconclusive because of the large experimental uncertainties. Regarding annihilation cross-sections, an alternative assumption of multiplicative type is proposed ; it cannot be tested with present data. The paper ends with a few final remarks. One of them deals with approximate $SU(3)$ invariance and shows that recent criticisms of Barger and Durand¹⁸⁾ against the quark model in its original form are avoided by the modification here proposed.

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I. - INTRODUCTION

Among the various relations between high energy cross-sections recently derived from the quark model ¹⁻⁸⁾, a distinction should be made between those which assume only the additivity property for quark amplitudes and those which require additional, "ad hoc" assumptions. If we restrict ourselves to spin-averaged total cross-sections, the most familiar relations of the former type are (P = proton, N = neutron)

$$S^+(PP) + S^+(PN) = 3 S^+(\pi^+P) \quad , \quad (1)$$

$$S^-(K^+P) - S^-(K^+N) = S^-(\pi^+P) \quad , \quad (2)$$

$$S^-(PP) - S^-(PN) = S^-(\pi^+P) \quad , \quad (3)$$

with the notation

$$S^\pm(AB) = G_T(\bar{A}B) \pm G_T(AB) \quad . \quad (4)$$

As to the second type, one has mainly the Freund relations ^{6),7),9)}

$$S^-(PP) = 5 S^-(\pi^+P) \quad , \quad (5)$$

$$S^-(PN) = 4 S^-(\pi^+P) \quad , \quad (6)$$

and the Levinson-Wall-Lipkin relations ⁸⁾

$$S^-(PP) = 2 S^-(K^+P) + S^-(K^+N), \quad (7)$$

$$S^-(PN) = S^-(K^+P) + 2 S^-(K^+N). \quad (8)$$

Relations (5) and (6) are equivalent if one has (3); similarly (7) and (8) are equivalent on the basis of (2) and (3). The "ad hoc" assumption required to obtain (5) and (6) is that the quark-quark and antiquark-quark "total cross-sections" satisfy

$$S^-(pn) = 0, \quad (9)$$

(we denote the three quarks by p, n, λ). To obtain (7) and (8) one needs the "ad hoc" assumption

$$S^-(\lambda p) = 0. \quad (10)$$

Neither of these assumptions is particularly natural in the framework of the quark model with additive amplitudes. Both should be regarded as expressing within the model the empirical facts that (5) - (6) are rather well and (7) - (8) very well satisfied by the data. We note that in the momentum range where they have been tested ($6 \leq p_T \leq 18$ GeV/c), the left-hand sides of relations (5) - (8) are overwhelmingly determined by the annihilation parts $\sigma_A(\bar{P}P)$, $\sigma_A(\bar{P}N)$ of the antinucleon-nucleon total cross-sections $\sigma_T(\bar{P}P)$ and $\sigma_T(\bar{P}N)$. Thus, any theoretical argument leading to a derivation of any of the relations (5) - (10) would relate antinucleon-nucleon annihilation cross-sections σ_A to non-annihilation effects.

We also note that the σ_A do not play such a dominant role in relations (1) - (3). They are absent in the very successful relation (2) and largely compensate each other in (3). In (1) they have a negligible effect at very high energy where $\sigma_A/\sigma_T \rightarrow 0$. At lower energies their contribution seems to be the main source of the imperfect agreement of (1) with experiment ⁵⁾. Indeed, the relation

$$2\sigma_T(PP) + 2\sigma_T(PN) = 3S^+(\pi^+P), \quad (11)$$

is in much better agreement with the data than (1), from which it differs by the quantity

$$S^-(PP) + S^-(PN) \simeq \sigma_A(\bar{P}P) + \sigma_A(\bar{P}N). \quad (12)$$

At $p_L \sim 14$ GeV/c, (12) is about 26 mb compared to ~ 160 mb for both sides of (11). This situation remains qualitatively unchanged if in (1) and (11) the left-hand and right-hand cross-sections are taken at laboratory momenta in the ratio $\frac{3}{2}$, as is needed to obtain approximately the same effective energy for the quark-quark collisions ^{3),5)}.

The preceding discussion implies that the additivity assumption of quark amplitudes has not been tested so far for the annihilation parts σ_A of the antibaryon-baryon cross-sections, and the excellent agreement of (11) as opposed to (1) with experiment suggests that additivity does not hold for σ_A . It is interesting that purely theoretical arguments point to the same conclusion. This is seen by using the unitarity condition in the form

$$2\sigma_T(AB) = \sum_n \langle AB | T^\dagger | n \rangle \langle n | T | AB \rangle, \quad (13)$$

where the sum extends over all elastic and inelastic final states of the $A + B$ collision (with energy momentum conservation taken into account), and where T is the properly normalized scattering operator. For $A = \bar{B}' =$ antibaryon, $B =$ baryon, the annihilation part $2\mathcal{G}_A$ of (13) is represented by diagrams of the type shown in Fig. 1, where the solid lines represent quarks and antiquarks and the wavy lines mesons. These diagrams have to be contrasted with those of Figs. 2a and 2b which must approximately describe the total sum (13) if the additivity assumption for quark amplitudes is valid. It is indeed unnatural to expect the contributions of Figs. 2 to provide good approximations to the annihilation process of Fig. 1. The reason is that the right-hand half of Fig. 1, representing $\langle \text{mesons} | T | \bar{B}'B \rangle$, contains exchange of a baryon, i.e., of three quarks, an effect not included in Figs. 2. A similar but less important limitation affects meson-nucleon scattering because it has in (13) a contribution from backward collisions corresponding to baryon exchange ; this contribution is quantitatively very small, however. Finally, for all hadrons A, B , we expect that only the diagrams of the type depicted in Fig. 2b and not those of Fig. 2a can provide a good approximation to the non-annihilation part of the sum (13). The reason is that the right-hand half of Fig. 2a contains quark-antiquark annihilation, i.e., a one-quark exchange process which experimentally has never been found to occur among the observed inelastic collisions $\langle n | T | AB \rangle$.

2. - ADDITIVITY WITHOUT ANNIHILATION

As suggested by the above discussion, we now apply additivity of the quark amplitudes to quantities $\tilde{S}^{\pm}(AB)$ defined as identical to $S^{\pm}(AB)$ when $A = \text{meson}$ and $B = \text{baryon}$, and as

$$\tilde{S}^{\pm}(AB) = S^{\pm}(AB) - \sigma_A(\bar{A}B) \quad , \quad (14)$$

when both A and B are baryons. The existing data concern the following cases $A = \pi^+, K^+, P$; $B = P, N$. We define analogous quantities $\tilde{S}^{\pm}(qq')$ for quarks q, q' , thereby excluding the antiquark-quark annihilation contribution of the type depicted in Fig. 2a.

Additivity gives

$$\begin{aligned} \tilde{S}^+(\pi^+P) &= \tilde{S}^+(\pi^+N) = 3 \tilde{S}^+(pp) + 3 \tilde{S}^+(pn) \quad , \\ \tilde{S}^-(\pi^+P) &= - \tilde{S}^-(\pi^+N) = \tilde{S}^-(pp) - \tilde{S}^-(pn) \quad , \\ \tilde{S}^{\pm}(K^+P) &= 2 \tilde{S}^{\pm}(pp) + \tilde{S}^{\pm}(pn) \pm 3 \tilde{S}^{\pm}(\lambda p) \quad , \\ \tilde{S}^{\pm}(K^+N) &= \tilde{S}^{\pm}(pp) + 2 \tilde{S}^{\pm}(pn) \pm 3 \tilde{S}^{\pm}(\lambda p) \quad , \\ \tilde{S}^{\pm}(PP) &= 5 \tilde{S}^{\pm}(pp) + 4 \tilde{S}^{\pm}(pn) \quad , \\ \tilde{S}^{\pm}(PN) &= 4 \tilde{S}^{\pm}(pp) + 5 \tilde{S}^{\pm}(pn) \quad , \end{aligned} \quad (15)$$

where the upper (or lower) signs have to be taken together. In (15) isospin and charge conjugation invariance are used.

By elimination of quark amplitudes one obtains

$$\tilde{S}^+(PP) + \tilde{S}^+(PN) = 3 \tilde{S}^+(\pi^+P) , \quad (16)$$

$$\tilde{S}^+(PP) - \tilde{S}^+(PN) = \tilde{S}^+(K^+P) - \tilde{S}^+(K^+N) , \quad (17)$$

$$\tilde{S}^-(PP) - \tilde{S}^-(PN) = \tilde{S}^-(\pi^+P) , \quad (18)$$

as well as

$$\tilde{S}^-(K^+P) - \tilde{S}^-(K^+N) = \tilde{S}^-(\pi^+P) . \quad (2')$$

As mentioned above, (16) agrees very well with experiment. The agreement of (17) and (18) with experiment is undecided because of the large uncertainties on the left-hand sides. As to (2'), it is identical to the "good" Johnson-Treiman relation (2) and is in excellent agreement with experiment. Thus, restricting ourselves to spin-averaged total cross-sections with exclusion of the annihilation parts, we find that the additivity assumption (with isospin and C invariance) predicts four relations, two of which are in excellent agreement with the facts while the others are fully compatible with them but have to await better data to be tested in a significant way.

We briefly mention typical values of the quark amplitudes following from measured hadron cross-sections. Equations (15) give at 10 GeV/c laboratory momentum

$$\begin{aligned} \tilde{S}^-(pp) &\simeq -\tilde{S}^-(np) \simeq 1 \text{ mb} , \quad \tilde{S}^-(\lambda p) \simeq -1.5 \text{ mb} \\ \tilde{S}^+(pp) &\simeq 9.5 \text{ mb} , \quad \tilde{S}^+(np) \simeq 7.7 \text{ mb} , \quad \tilde{S}^+(\lambda p) \simeq 4.4 \text{ mb} \end{aligned} \quad (19)$$

One obtains for the spin-averaged quark "total cross-sections" $\tilde{a}(qq')$, excluding annihilation contributions

$$\begin{aligned} a(\bar{p}p) &\simeq 5.25 \text{ mb}, \quad a(pp) \simeq a(np) \simeq 4.25 \text{ mb}, \\ a(\bar{n}p) &\simeq 3.25 \text{ mb}, \quad a(\lambda p) \simeq 3 \text{ mb}, \quad a(\bar{\lambda}p) \simeq 1.5 \text{ mb}. \end{aligned} \quad (20)$$

The signs of the $\tilde{S}^-(qq')$ deserve a comment. One expects that for quarks as for hadrons the sign of $\tilde{S}^-(q')$ is positive if more charge and/or hypercharge exchange channels are open to $\bar{q} + q'$ than to $q + q'$ collisions. This rule applies quite well to hadrons⁵⁾. For quarks and antiquarks it predicts

$$\tilde{S}^-(pp) > 0, \quad \tilde{S}^-(np) < 0, \quad \tilde{S}^-(\lambda p) < 0, \quad (21)$$

(remember that only integral charge and hypercharge can be exchanged). Equations (19) agree with these predictions *).

*)

One might say that this provides a consistency check for the notion that in (15) only the non-annihilation parts $\tilde{S}^\pm(qq')$ occur, in the sense that if one would have found $\tilde{S}^-(np)$ or $\tilde{S}^-(\lambda p)$ positive this would have been an indication that $S^\pm(qq')$ rather than $\tilde{S}^\pm(qq')$ should have occurred in (15).

3. - QUARKS AND HIGH ENERGY ANNIHILATION

Having abandoned the additivity assumption of quark amplitudes for the annihilation part $\sigma_A(\bar{B}'B)$ of antibaryon-baryon cross-sections, we are faced with the question of how the quark structure of baryons would manifest itself in annihilation at high energy. The quark rearrangement scheme proposed by Rubinstein and Stern for low energy ^{10), 11)} does not seem to give a satisfactory answer to this question. For high energy annihilation, the simplest model we can propose is based on the assumption that the antibaryon-baryon annihilation amplitudes approximately factorize into the product of three antiquark-quark annihilation amplitudes, momentum and energy being approximately conserved in each of the latter. This amounts to approximating Fig. 1 by Fig. 3. One must suppose that interaction and exchange effects between the mesons produced in annihilation do not impair the approximation too much, at least for a quantity like $\sigma_A(\bar{B}'B)$ which is integrated over all annihilation states. Our assumption is compatible with the fact that the dominant annihilations in flight are found experimentally to be into channels with six or more mesons (counting resonances as single mesons) ¹²⁾.

The factorization assumption for $\bar{B}'B$ annihilation is mathematically expressed as follows

$$\sigma_A(\bar{B}'B) = \sum_{\{j_1, j_2, j_3\}} \prod_{i=1,2,3} Z(j_i, i), \quad (22)$$

where j_1, j_2, j_3 run over the permutations of 1, 2, 3 and $Z(j_i, i)$ describes the contribution of all annihilations of antiquark j_i in $\bar{B}'$ with quark i in B (see Fig. 3). Z is the product of an antiquark-quark annihilation cross-section and a factor determined by the wave function of the baryon as bound state of three quarks.

We assume this factor to be the same for all baryons. Writing

$$Z_1 = Z(\bar{p}p), \quad Z_2 = Z(\bar{p}n), \quad Z_3 = Z(\bar{\lambda}p), \quad (23)$$

and using isospin and charge conjugation invariance, one then finds

$$\begin{aligned} \sigma_A(\bar{p}p) &= 2 Z_1^3 + 4 Z_1 Z_2^2, \\ \sigma_A(\bar{n}p) &= 2 Z_2^3 + 4 Z_1 Z_2^2, \\ \sigma_A(\bar{\lambda}p) &= \sigma_A(\bar{\Sigma}^0 p) = 2 Z_1 Z_2 Z_3 + 2 Z_1^2 Z_3 + 2 Z_2^2 Z_3, \\ \sigma_A(\bar{\Sigma}^+ p) &= 2 Z_1^2 Z_3 + 4 Z_1 Z_2 Z_3, \\ \sigma_A(\bar{\Sigma}^- p) &= 2 Z_2^2 Z_3 + 4 Z_1 Z_2 Z_3, \\ \sigma_A(\bar{\Xi}^- p) &= 2 Z_1 Z_3^2 + 4 Z_2 Z_3^2, \\ \sigma_A(\bar{\Xi}^0 p) &= 2 Z_2 Z_3^2 + 4 Z_1 Z_3^2, \\ \sigma_A(\bar{\Omega}^- p) &= 6 Z_3^3, \end{aligned} \quad (24)$$

and similar equations for the other members $\bar{N}^*$, $\bar{Y}^*$, $\bar{\Xi}^*$ of the antidecuplet. Tests of these relations will only become possible through observation of antihyperon annihilation in flight.

The empirical relations (5) - (8) imply in the present model the following relations between quark annihilation and non-annihilation cross-sections :

10.

from (5) and (6)

$$Z_1^3 = Z_2^3 = -\frac{3}{2} \tilde{S}^-(np) , \quad (25)$$

and from (7) and (8)

$$Z_1^3 = Z_2^3 = -\frac{3}{2} \tilde{S}^-(\lambda p) . \quad (26)$$

Remember that both right-hand sides are positive, see (21).

Simultaneous validity of relations (5) - (8) requires

$$\tilde{S}^-(np) = \tilde{S}^-(\lambda p) , \quad (27)$$

which is precisely the condition needed to obtain from (15) the "second" Johnson-Treiman relations

$$\frac{1}{2} \tilde{S}^-(K^+P) = \tilde{S}^-(\pi^+P) . \quad (28)$$

One knows that it is less well satisfied by the data than the "first" relations (2), just as relations (5), (6) are less well satisfied than (7), (8). Finally, introduced in (24), the equality $Z_1^3 = Z_2^3$ implied by (25) or (26) leads to the result that the annihilation cross-sections $\sigma_A(\bar{B}P)$ do not depend on the isospin and charge of $\bar{B}$, but only on its strangeness. Denoting $\sigma_A(\bar{B}P)$ by $\sigma_A(S)$ for strangeness S of $\bar{B}$, one finds

$$\frac{\sigma_A(0)}{\sigma_A(1)} = \frac{\sigma_A(1)}{\sigma_A(2)} = \frac{\sigma_A(2)}{\sigma_A(3)} . \quad (29)$$

4. - CONCLUDING REMARKS

We end with a few remarks on various questions raised by the preceding discussion.

A) - As far as observable predictions are concerned, the main difference between the original version of the additivity assumption for quark amplitudes and the modified model here proposed lies in the fact that in the modified model baryon-antibaryon annihilation processes are kept separate from all other high energy processes. The original model predicts relations between these classes of processes, e.g.,

$$S^-(\Omega^-P) = S^-(PP) - 2S^-(K^+P) - S^-(K^+N) \quad (30)$$

The right-hand side of (30) vanishes on the basis of (7). The modified model, on the other hand, keeps $\sigma_A(\bar{\Omega}^-P) = 6Z_3^3$ independent from the non-annihilation processes described in terms of the quantities (14). It should be noted, however, that if $Z_1 \simeq Z_2 \simeq Z_3$ (i.e., all $\sigma_A(\bar{B}'B)$ are equal), the annihilation contributions in relations of type (30) cancel out. As mentioned in the previous section, present data suggest $Z_1 \simeq Z_2$. The further equality $Z_1 \simeq Z_3$ can only be checked by measuring $\sigma_A(\bar{Y}P)$ at high energy for some hyperon Y .

B) - Our discussion has dealt only with the imaginary part of the forward scattering amplitudes. For each pair of reactions $B'+B \rightarrow B'+B$ and $\bar{B}'+B \rightarrow \bar{B}'+B$ the real and imaginary parts of the corresponding forward amplitudes T and $\bar{T}$ are related by crossing relations. This implies that, depending on the power α of s in the second term of the asymptotic series ^{13), 14)}

$$T \underset{s \rightarrow +\infty}{=} c_1 s + c_2 s^\alpha + \dots, \quad \alpha \text{ real}, \quad c_1 \simeq i|c_1|,$$

$$\bar{T} \underset{s \rightarrow +\infty}{=} -c_1^* s + c_2^* e^{-i\pi\alpha} s^\alpha + \dots,$$

the exclusion of annihilation processes from the additivity assumption for $\text{Im } \bar{T}$ will affect the validity of additivity for T as well as for $\text{Re } \bar{T}$. For $\alpha \simeq \frac{1}{2}$ mainly $\text{Re } T$ is affected, for $\alpha \simeq 0$ mainly $\text{Im } T$. The latter case would lead to an inconsistency because under our assumption additivity holds for the imaginary part of the whole amplitude T , and this then would imply the same for $\text{Im } \bar{T}$ including annihilation contributions. Fortunately, the present data on PP and $\bar{P}P$ scattering at high energy are fully compatible with the value $\alpha = \frac{1}{2}$ (14), (15). A more precise experimental determination of α will therefore provide an important test of the present considerations. As to the non-forward amplitudes, the simplest presentation of the modified model will again be based on the unitarity condition (13), now taken for non-vanishing momentum transfer, additivity of quark amplitudes being restricted to the non-annihilation contribution to the right-hand side.

C) - In Eqs. (19) and (20) we have given the numerical values of quark "total cross-sections" derived from 10 GeV/c data under the modified additivity model. One immediately notices a few simple empirical relations between them :

$$a(pp) \simeq a(np) \quad , \quad (31)$$

$$\tilde{S}^+(pp) + \tilde{S}^+(np) \simeq 4 \tilde{S}^+(\lambda p) \quad , \quad (32)$$

$$\tilde{S}^-(pp) + \tilde{S}^-(np) \simeq 0 \quad . \quad (33)$$

On the basis of available data, Eqs. (31) - (32) hold in the interval $6 \leq p_L \leq 18$ GeV/c. Equation (31) reflects the well-known approximate equality of $\sigma_T(K^+p)$ and $\sigma_T(K^+N)$; it can be understood in the Regge pole model in terms of Arnold's proposal of exchange degeneracy¹⁶⁾. Equation (32) is surprisingly well satisfied and corresponds to^{*)}

$$3 \tilde{S}^+(\pi^+P) = 2 \left[\tilde{S}^+(K^+P) + \tilde{S}^+(K^+N) \right] \quad (34)$$

Equation (33), which reflects the relation

$$\tilde{S}^-(PP) + \tilde{S}^-(PN) \simeq 0, \quad (35)$$

is only roughly valid because of the uncertainty on annihilation cross-sections. Neither (32) nor (33) have been given simple dynamical interpretations.

D) - The next remark is of a more general nature. Our theoretical argument against including annihilation effects in the quark model with additive amplitudes rests on the fact that these effects correspond to baryon exchange. At high energy ($p_L \gtrsim 5$ GeV/c), they are the only baryon exchange processes having a cross-section $\gtrsim 1$ mb. All other hadron collision processes of sizable cross-section at high energy are of very different type, corresponding to exchange of vanishing baryon number. It may therefore be that no dynamical model would give a successful unified description of both types of processes, not even of their contribution to the total cross-sections. A similar conjecture is expressed in a recent paper by Biaľas and Zalewski¹⁷⁾, who direct it in particular against applicability of the Regge pole model to the annihilation part of the baryon-antibaryon total cross-sections. The model presented in Sections 2 and 3 of the present

*) Extrapolating (32) and using the Pomeranchuk theorem for quarks, one gets $\sigma_T(PP) : \sigma_T(\pi P) : \sigma_T(KP) = 6 : 4 : 3$ in the limit $s \rightarrow \infty$.

paper gives an example of a situation where different mechanisms control the annihilation and non-annihilation parts of the cross-sections. The latter, because of additivity of quark amplitudes, are compatible with quark-antiquark exchange, i.e., with exchange of meson Regge trajectories of singlet and octet character. The annihilation cross-sections on the contrary, if expressed by (24), require in general exchange of higher $SU(3)$ multiplets; this is for example the case if $Z_1 = Z_2 \neq Z_3$, unless one neglects $(Z_3 - Z_1)^2$ compared to $Z_3 - Z_1$; experimentally, a decision on this question can only be reached by measuring antihyperon-proton annihilation cross-sections at high energy.

E) - We end with some comments on approximate $SU(3)$ symmetry and show that the additivity model here advocated avoids the criticisms recently raised by Barger and Durand¹⁸⁾ against additivity in its original form. For the quark amplitudes, $SU(3)$ symmetry implies the two relations

$$\tilde{S}^{\pm}(np) = \tilde{S}^{\pm}(\lambda p) . \quad (36)$$

The numerical values (19) show that these relations are seriously violated. Assuming nevertheless their validity, we derive from (15) two additional relations between known cross-sections, one of which is (28) and the other one

$$\tilde{S}^+(pp) = 2 \tilde{S}^+(\pi^+p) - \frac{1}{2} \tilde{S}^+(K^+p) . \quad (37)$$

These relations are in approximate agreement with the data, the discrepancy at 10 GeV/c being of order of 1 mb between the two sides of (28) and of 3 mb between those of (37). The relative discrepancy is of course high in relation (28) since its two sides are very small,

$$\tilde{S}^-(\pi^+p) = 1.7 \pm 0.4 \text{ mb} , \quad \tilde{S}^-(K^+p) = 5.2 \pm 0.3 \text{ mb} .$$

The discrepancy in (37) becomes much larger, of order 10 mb, if $\tilde{S}^+(\text{PP})$ is replaced by $S^+(\text{PP})$ as would be required in the original additivity model. This fact and the good agreement of (16) with the data show that our modified model is free of the difficulties stressed by Barger and Durand for total cross-sections. The latter authors consider in addition forward differential cross-sections for charge-exchange reactions, in particular the relations ³⁾

$$\frac{d\sigma}{dt}(\bar{\text{P}}\text{P} \rightarrow \bar{\text{N}}\text{N}) = \frac{d\sigma}{dt}(\text{K}^-\text{P} \rightarrow \bar{\text{K}}^0\text{N}) ,$$

$$\frac{d\sigma}{dt}(\text{P}\text{N} \rightarrow \text{N}\text{P}) = \frac{d\sigma}{dt}(\text{K}^+\text{N} \rightarrow \text{K}^0\text{P}) .$$

It should first be stressed that the relations only hold in the original additivity model if the amplitudes are spin-independent, which is not necessarily true even at $t = 0$ for the left-hand side reactions. In our modified model, the relations do not hold even for spin-independent amplitudes. Indeed, the forward $\text{PN} \rightarrow \text{NP}$ amplitude is dominantly real ^{19), 20)} and is therefore affected by lack of additivity as explained in remark B) above, whereas $\bar{\text{P}}\text{P} \rightarrow \bar{\text{N}}\text{N}$ is dominantly imaginary ^{17), 20)} and is affected by annihilation effects ¹⁷⁾, meaning again lack of additivity. Forward strangeness exchange and γ production reactions, the latter also discussed by Barger and Durand, cannot test additivity without additional assumptions.

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FIGURE CAPTIONS

- Figure 1 Diagram representing antibaryon-baryon annihilation contributions to the sum in (13).
- Figure 2 Diagrams describing, for antibaryon-baryon scattering, the sum in (13) under the additivity assumption for quark amplitudes, with (diagram a) and without (diagram b) quark-antiquark annihilation. Similar diagrams can be drawn for baryon-baryon and meson-baryon scattering.
- Figure 3 Diagram showing the factorization of antibaryon-baryon annihilation into three antiquark-quark annihilations.

FIG.1

FIG.2

FIG.3

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A D D E N D U M

The following paragraph should be added on page 4 at the end of Section 1 :

The only annihilation cross-section measured so far at high energy is $\sigma_A(\bar{P}P)$ at $p_L = 5.7 \text{ GeV}/c$ ¹²⁾. It verifies

$$\sigma_A(\bar{P}P) = 22.5 \pm 2 \text{ mb} \simeq S^-(PP) = 21.5 \pm 1 \text{ mb}.$$

It seems reasonable to assume that for $p_L \gtrsim 6 \text{ GeV}/c$, one has

$$\sigma_A(\bar{P}P) \simeq S^-(PP), \quad \sigma_A(\bar{P}N) \simeq S^-(PN),$$

with errors of the order of one or two millibarns. This assumption will allow us to compare our further theoretical considerations with experiment.