# PROGRESS IN ANTIPROTON PHYSICS* 

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## ABSTRACT

Some recent results on proton-antiproton collisions are reviewed. The duality structure of processes where baryon number or strangeness may be annihilated receives particular attention. Attempts to obtain experimental information on the impact parameter space structure of multiparticle processes are discussed. Suggestions for future research are made.

## I. INTR ODUCTION

Since the late sixties it has been known that baryon-antibaryon $(\mathrm{B} \overline{\mathrm{B}}$ ) interactions in which the baryon number is annihilated possess several unusual properties and do not fit easily into the theoretical framework of duality and Regge behaviour which has been so successful in the analysis of other hadronic collisions. The application of the standard duality ideas into $B \bar{B}$ annihilation immediately yields the prediction that in these processes exotic resonances should be produced. By exotic resonances we mean here mesonic states (a) which do not possess the normal $\bar{Q} \bar{Q}$ quark structure of mesons and (b) whose coupling to baryon-antibaryon channels is substantially larger than to channels made up by normal meson resonances ( $\pi, \rho, \omega, \mathrm{f}, \mathrm{A}_{2}, \ldots$ ). This duality prediction was once thought to be theoretically so disturbing that it was called by Harari the "duality catastrophe".

In this talk I shall discuss the problem of the duality structure of $\mathrm{B} \overline{\mathrm{B}}$ collisions. I shall, in particular, try to emphasize the following question: What new can we learn about duality and hadron structure by studying $B \bar{B}$ interactions that we can't learn from experiments done with pion, kaon, or proton beams? I shall first describe very briefly some of the ingredients of what I call the "standard duality approach" to hadron collisions. Next, I illustrate this approach by applying it to the "strangeness annihilation" processes $K \bar{K} \rightarrow$ pions. These processes are analogous to baryon number annihilation processes $\mathrm{B} \overline{\mathrm{B}} \rightarrow$ pions but much simpler to analyze, since here the initial state has the quark structure $(Q \bar{Q})+(Q \bar{Q})$ instead of the much more complicated quark structure $(\mathrm{QQQ})+(\bar{Q} \bar{Q} \bar{Q})$ of the latter processes. Section IV is devoted to the problem of the duality structure of the $B \bar{B}$ amplitudes. I shall try to outline the problem and to review some of the recent suggestions for solutions. One of our conclusions is that there is a compelling theoretical need for exotic "baryonium" states in $\bar{B} \bar{B}$ annihilations. This point will be further discussed by Professor Chew in his talk tomorrow. $\overline{H e}$ will also discuss the expected properties of these states and review the experimental evidence for their existence. In Section $V$ we study the impact parameter space

[^0]distribution of the NN processes. Section VI presents some brief remarks on nonannihilation processes. Finally, an attempt is made to suggest some promising directions for future research.

## II. THE STANDARD DUALITY APPROACH

The following is a very brief summary only, intended to remind you of some of the "rules of the game". Excellent reviews of the many applications of duality are given in (Refs 1-3).

- Quark structure. Hadrons are built up by quarks. All mesons are bound states of a quark and an antiquark. All baryons (antibaryons) are bound states of three quarks (antiquarks). Quarks come in four flavours ( $u=u p, d=d o w n, \lambda=s t r a n g e$, and $\mathrm{c}=$ charm). Each quark flavour comes in three colours. Although colour is a very important property of quarks, for the rest of this talk you may forget that it exists. Furthermore, we ignore here the spins of the quarks, the detailed structure of the hadrons, as well as the problem of quark confinement. We describe a quark propagating forward in time by a directed line: $\longrightarrow$ — . Similarly, for an antiquark we have: $\longleftarrow$. Thus, for example,


Interactions among hadrons are due to interactions among their constituent quarks. There are three basic types of quark interactions: (i) annihilation, (ii) pair creation, and (iii) rearrangement. Examples:


Duality diagrams. What we have drawn above are examples of duality diagrams. They specify the particular quark properties of the hadronic amplitudes which have to be obeyed in order to guarantee that duality, resonance dominance (of imaginary parts of nondiffractive amplitudes), and the absence of exotic states are valid. The rules for drawing these diagrams are simple:
I. Each quark line retains its identity.
II. Only the topology of the diagram matters, not the particular way the diagram is drawn.
III. Disconnected diagrams are suppressed.

Rule II states that, for example, the following two diagrams are equivalent:


This equation gives a graphical illustration of the principle of duality: Resonances in the direct channel build up Regge poles in the crossed channel. Rule III is the famous Okubo-Zweig-Iizuka (4) rule. To give an example of this rule, consider the following two diagrams for $\mathrm{e}^{+} \mathrm{e}^{-} \rightarrow$ hadrons:
a)

b)


Diagram a is "Zweig allowed" whereas the disconnected diagram $b$ is "Zweig forbidden". Notice, however, that below the charm production threshold ( $\mathrm{E}_{\mathrm{th}}=2 \mathrm{~m}_{\mathrm{D}}=$ $2(1.865 \mathrm{GeV})=3.73 \mathrm{GeV})$ the "legal" diagram a is kinematically forbidden. Since the masses of the cc states $\psi$ and $\psi^{\prime}$ lie below this threshold, these states must decay either through the Zweig rule violating mechanism b or electromagnetically. This is the popular quark diagram explanation for the long lifetimes of these states.

- S-channel unitarity. This is a most important ingredient of our approach and is expressed through the following equation:

$$
\operatorname{Im} T_{a b \rightarrow c d}=\sum_{n}\langle c d| T^{+}|n\rangle\langle n| T|a b\rangle
$$

Here, the sum runs over all the intermediate states $|n\rangle$ which couple both to the aband to the cd-channels.

- Two-component duality. This principle says that a general description of hadronic amplitudes is given in terms of two additive components:

Component I: Direct channel resonances build up Regge poles in the crossed channels. The unitarity equation for this component, drawn in terms of duality diagrams, looks as follows:


Component II: Nonresonant background in the s-channel builds up the Pomeranchuck amplitude in the crossed channel. Again, in terms of duality diagrams we have:




t-channel

Regge model interpretation. Consider a two-body process $a b \rightarrow c d$. In the Regge limit of large energy $s$ and small momentum transfer $t$ we expect the amplitude of this process to be dominated by exchange of Regge poles in the t-channel. To satisfy duality, we give the following interpretation to the duality diagrams: A diagram with $Q \bar{Q}$ annihilation and recreation in s-channel (no twists of quark lines in t -channel) represents an amplitude which is dominated by the exchange of an ex-change-degenerate pair of Regge poles in the t-channel. The phases of the individual pole amplitudes are such that the net amplitude has a purely rotating phase:


An s-channel rearrangement diagram (quark lines twist in the $t$-channel) is dominated by the same EXD Regge poles as the above diagram. Now, however, the net amplitude has a purely real phase (we denote this by a twist $k$ ):



To give an example, consider $\pi \pi$ scattering. In $\pi^{+} \pi^{-}$scattering, the Regge amplitudes f and $\rho$ add, tơ give a purely imaginary amplitude; in $\pi^{+} \pi^{+}$scattering they subtract, resulting in a purely real amplitude:


- Counting the number of diagrams (Ref. 5). To make the discussion as transparent as possible, let us consider a production process $a+b \rightarrow 1+\ldots+n$ in the multiRegge limit where all the sub-energies $s_{i}$ are large and all the momentum transfers $t_{i}$ are small. We make the strong-ordering approximation $t_{i} \approx t_{i}$, where $\mathrm{t}_{\mathrm{i}_{\perp}}$ is the transverse part of the momentum transfer, integrate over the transverse momenta, and analyze the resulting one-dimensional unitarity equation:


The intercepts of the input and output Regge trajectories are related as follows:

$$
\alpha_{\text {out }}=2 \alpha_{\text {in }}-1+\mathrm{g}^{2}
$$

We now draw all possible duality diagrams for the multi-Regge amplitudes and use our previous interpretation which associated a diagram with (without) twist with a real (rotating) phase of the Regge amplitude. We see that for each n particle final state there is only one diagram which contributes to building up the Reggeon trajectory, namely, that one which has no twists at all:

while there are numerous diagrams with twists:


All the $2^{\mathrm{n}}-1$ twisted diagrams contribute to the building up of the Pomeranchuck singularity. Let us then assume that we may ignore the interference terms in the unitarity equation, e.g., diagrams like

and keep only the diagonal elements. Since the only difference between a twisted and a non-twisted amplitude is in their phase, and the phase drops out when an amplitude is squared, we see that the contribution of a diagram to the unitarity sum is independent of the number of twists in this diagram. Summing up all the twisted diagrams one obtains the result that their sum is equivalent to the contribution of a single diagram, its coupling constant squared being "renormalized" by a factor of two: $\mathrm{g}^{2} \rightarrow 2 \mathrm{~g}^{2}$. Thus we have

$$
\begin{align*}
& \alpha_{\mathrm{M}}=2 \alpha_{\text {in }}-1+\mathrm{g}^{2},  \tag{1a}\\
& \alpha_{\mathrm{P}}=2 \alpha_{\mathrm{in}}-1+2 \mathrm{~g}^{2} . \tag{1b}
\end{align*}
$$

If we now impose the "bootstrap" condition that $\alpha_{\text {in }}=\alpha_{M}$, we obtain from. Eqs. (1a) and (1b):

$$
\alpha_{\mathrm{P}}=1!!
$$

Although this surely looks like a numerical accident (think about all the approximations we made), it teaches us an important lesson: The much larger number of nonresonant than resonant multiparticle amplitudes "promotes" the intercept of the output Pomeron trajectory to lic above that of the output meson trajectory.

The incorporation of duality and unitarity into one unified scheme has been under intensive study in the past few years. Several groups of theorists have developed extensive schemes to accomplish this and many interesting results have been obtained. In the above we have discussed on a very naive level some of the ideas which underlie these schemes. We shall say more about these schemes in Section IV. Here we confine ourselves to giving a (necessarily incomplete) list of references to original work (6-9) and to some useful review articles (10).

## III. KK̄ SCATTERING AND STRANGENESS ANNIHILATION

Strangeness annihilation processes, such as

$$
\begin{equation*}
\mathrm{K} \overline{\mathrm{~K}} \rightarrow \text { pions } \tag{2}
\end{equation*}
$$

are analogous to baryon number annihilation processes, but have much simpler quark structure. Before turning to the complex problem of $B \bar{B}$ annihilation, let us test our quark diagram method by applying it to strangeness annihilation (11). By drawing the duality diagrams for the above process and performing the unitarity summation

$\phi$ exchange

$$
\alpha_{\phi}(0) \approx 0
$$

we see that (a) the annihilation process should always proceed via production and decay of resonances (i.e., there should be no nonresonant background) and (b) the produced resonances should be dual to a Regge singularity with the quark content of $\lambda \bar{\lambda}$ in the crossed channel of the elastic amplitude. The leading singularity with this quark content is the exchange degenerate $\mathrm{f}^{\prime}-\phi$ trajectory with intercept $\alpha_{\phi} \approx 0$. Hence one expects the total annihilation process to die away rapidly with increasing energy $(\sigma(K \bar{K} \rightarrow$ pions $) \sim .1 / s)$.

The nonannihilation processes of the type

$$
\begin{equation*}
\mathrm{K} \overline{\mathrm{~K}} \rightarrow \mathrm{~K} \overline{\mathrm{~K}}+\text { pions } \tag{3}
\end{equation*}
$$

are expected to obey normal duality, i.e., resonances being dual to the ordinary meson trajectories with intercept $\alpha_{M}(0)=0.5$ :


$$
\begin{aligned}
& f, \rho, \omega, A_{2} \\
& \alpha_{M^{(0)}}=\frac{1}{2}
\end{aligned}
$$

and background being dual to the Pomeron:

$=$


Guided by these considerations we write for the total cross section of $K \bar{K}$ scattering

$$
\begin{equation*}
\sigma_{\text {tot }}(\mathrm{K} \overline{\mathrm{~K}})=\mathrm{A}+\mathrm{B} \frac{1}{\sqrt{\mathrm{~s}}}+\mathrm{C} \frac{1}{\mathrm{~s}} . \tag{4}
\end{equation*}
$$

The first two terms correspond to the nonannihilation processes (3) and the third term to the annihilation process (2).

How to test these ideas experimentally? Direct tests are, of course, not possible, since we do not have kaon targets available. However, it is possible to obtain information on the forward amplitude when one of the kaons is a Reggeon. For inclusive reactions in the appropriate Regge region, the cross section is related, through the generalized optical theorem, to the Reggeon-particle forward scattering amplitude. Hence we can indirectly study the dual properties of $K \bar{K}$ scattering by considering an inclusive process such as $\mathrm{K}^{-} \mathrm{p} \rightarrow \Lambda+\mathrm{X}$ which is proportional to $\mathrm{K}^{*}$ (or K ) Reggeon- $\overline{\mathrm{K}}$ scattering which, in turn, should exhibit similar duality behaviour.

Figure 1 presents a compilation of cross sections in the proton fragmentation region of the processes

$$
\begin{align*}
& K^{-} p \rightarrow \Lambda+X  \tag{5}\\
& a+p \rightarrow \Lambda+X ; \quad a=p, \pi^{+}, K^{+} \tag{6}
\end{align*}
$$

$$
\begin{equation*}
a+p \rightarrow \Lambda+X ; \quad a=\bar{p}, \pi^{-}, \gamma \tag{7}
\end{equation*}
$$

Factorization allows us to estimate the Pomeron and meson exchange contributions to the process (5) from the cross sections of the processes (6) and (7). These estimates are shown in the figure. We see that the spectrum for the process (5) lies considerably above these estimates. Moreover, the difference between the measured spectrum


Fig. 1. Normalized invariant cross sections of various inclusive $\Lambda$ production processes integrated over the $x$-interval $-0.9 \leq x \leq-0.5$ as a function of $\mathrm{s}^{-1}$. The theoretical interpretation of the data is indicated in the figure [the dash-dotted (dash-double dotted) line represents the sum of the Pomeron and meson contributions in $\mathrm{K}^{-} \mathrm{p}\left(\pi^{-} \mathrm{p}\right)$ process]. The errors shown include systematic uncertainties when available as well as statistical errors. (From Ref. 11.)
and the Pomeron and meson contributions is seen to decrease rapidly with increasing energy, indicating a low intercept of the corresponding trajectory in the $\mathrm{K} \overline{\mathrm{K}}$ channel. A quantitative estimate gives $\alpha(0) \approx 0$, consistent with Eq. (4).

The Amsterdam-CERN-Nijmegen-Oxford Collaboration (12) has carried out a detailed study of the properties of the process (5) using their high statistics 4.25 $\mathrm{GeV} / \mathrm{c}$ data. Figure 2 shows the observed missing mass distribution recoiling against the $\Lambda$ in the proton fragmentation region $\left(\left|t_{\mathrm{p} \Lambda}\right|<1 \mathrm{GeV}^{2}\right.$ ). Below the $\mathrm{K} \overline{\mathrm{K}}$ production threshold we see strong resonance signals with relatively little background. This supports the quark diagram prediction that the annihilation process should proceed mainly via production and decay of resonances. An interesting new result concerns the $\Lambda$ polarization (13). Figure 3 shows the polarization of the $\Lambda$ in the processes $K^{-} \mathrm{p} \rightarrow \Lambda+\pi^{\prime}$ s and $\mathrm{K}^{-} \mathrm{p} \rightarrow \Lambda+\mathrm{K} \overline{\mathrm{K}}$ $+\pi$ 's in the proton fragmentation region $(-1<x<-.2)$. It is seen to be clearly different in the two cases. Many other interesting results were obtained, too. However, since the results of this analysis


Fig. 2. Mass distribution $\mathrm{M}_{\mathrm{X}}$ of the reaction $\mathrm{K}^{-} \mathrm{p} \rightarrow \Lambda^{0}+\mathrm{X}$ in the target fragmentation region. (From Ref. 12.)

have already been reviewed at several occasions (14), I shall not discuss them further here.

The Athens-Liverpool-Demokritos-Vienna Collaboration has systematically compared the properties of baryon ( $B \bar{B}$ ), strangeness ( $K \bar{K}$ ), and $\mathrm{e}^{+} \mathrm{e}^{-}$annihilation processes (15). Strong similarities between these processes were observed. Dr. J. Fry will give a detailed report on these results on Tuesday (16).

Fig. 3. $\Lambda^{\circ}$ polarization as a function of the transverse momentum $p_{T}$ for the target fragmentation region $-1.0<x$ $<-0.2$. (a) Data points refer to $\mathrm{K}^{-}$ $+\mathrm{p} \rightarrow \Lambda+$ pions and $O$ refer to $\mathrm{K}^{-}+\mathrm{p}$ $-\Lambda+K \bar{K}+$ pions. (From Ref. 13.)

## IV. B $\bar{B}$ SCATTERING AND BARYON NUMBER ANNIHILATION

In $B \bar{B}$ scattering, the quark structure of the initial state is $(Q Q Q)+(\bar{Q} \bar{Q})$. It is easy to see that the legal duality diagrams fall into five different classes as follows:

- Non-Annihilation. Here we have two different types of diagrams, analogous to the diagrams drawn in Section II.


We see that type I diagrams build up a normal $Q \bar{Q}$ trajectory in the t-channel. This trajectory, however, is dual to direct channel mesonic states with the exotic $Q Q \bar{Q} \bar{Q}$ quark content. Since these states should couple strongly only to $B \bar{B}$ channels, they have been dubbed "baryonium" states, in analogy to positronium and charmonium.

The existence of such states is an unavoidable prediction of duality (17), and it may be regarded either as a triumph or as a catastrophe for duality, depending on whether they are found or not. A detailed discussion of their expected properties is presented by Professor Chew (18). Another detailed and very interesting analysis of such states is given by Bob Jaffe in three recent preprints (19). He calculates their spectra and dominant decay couplings in the MIT quark bag model. He suggests that certain known $0^{+}$-mesons ( $\left.\epsilon(700), \mathrm{S}^{*}, \delta, \kappa\right)$ may have been commonly misclassified and in fact belong to the lowest $Q Q \bar{Q} \bar{Q}$ nonet. His interpretation of these states is, however, somewhat different from that of Professor Chew and myself, since he doesn't associate these states in any particular way with the baryon-antibaryon channel.

- Annihilation. There are three types of diagrams:


How should one interpret these diagrams? For diagram III the interpretation is clear: here we have normal (i.e., $Q \bar{Q}$ ) s-channel resonances building up a "baryonium" trajectory in the t-channel. The well-known analysis of Hoyer, Roberts, and Roy (20) lends support to such an interpretation. Diagrams IV and V are harder to interpret. Looking first at the left-hand side we see that they both correspond to nonresonant background amplitudes. We shall call these two kinds of backgrounds "diffuse" (IV) and "dense" (V) since the former is expected to have a lower average multiplicity than the latter. The diffuse background builds up a trajectory with the $Q \bar{Q}$ quark content in the t-channel, while that built up by the dense background has the quark content of the vacuum. A naive application of the quark diagram counting argument gives us the result that the intercepts of the output trajectories are ordered as follows:

$$
\begin{equation*}
\alpha_{\mathrm{V}}(0)>\alpha_{\mathrm{IV}}(0)>\alpha_{\mathrm{III}}(0) . \tag{8}
\end{equation*}
$$

There are at least three different suggestions for the interpretation of the diagrams IV and V :

1. The "Classical" Solution. The component IV builds up a normal meson trajectory ( $\alpha_{M}(0)=1 / 2$ ) in the t-channel. Experimentally, however, the total annihilation cross section seems to decrease as $p_{l a b}^{-\frac{1}{2}}$ (see J. Rushbrooke's review (21)). Eq. (8) then implies that, for some unknown reason, the component $V$ is suppressed and the component IV dominates the annihilation cross section.
2. The Eylon-Harari Solution (22). The observation that the amplitude built up by type $V$ diagrams has no quarks exchanged in the t-channel leads one naturally to consider the possibility that the output singularity is either a daughter of the Pomeron or a part of the Pomeron singularity itself. Indeed, Eylon and Harari pointed out that if the annihilation diagrams III-V were ignored, the Pomeron contributions to protonproton and proton-antiproton scattering would be different. This is easy to see: In proton-proton scattering, for an $n+1$ particle final state, all the $2^{n}$ diagrams have twists in them and thus contribute to the Pomeron amplitude. In proton-antiproton scattering, however, only $2^{\mathrm{n}}-1$ of the diagrams have twists and contribute to the Pomeron, the missing diagram being the totally untwisted diagram of type I and contributing to the Reggeon amplitude. Thus, one faces the following interesting situation: One has a piece "missing" from the Pomeron in $B \bar{B}$ scattering, and, at the same time, an extra "Pomeron-like" contribution $V$ which exists in $B \bar{B}$ scattering but does not exist in BB scattering. To make the pieces of this puzzle fit Eylon and Harari assumed that the leading annihilation term V is indeed the "missing Pomeron piece". The full duality structure of $B \bar{B}$ scattering, including the non-annihilation processes, is then as follows:

3. Webber's Scheme (23). An important point, ignored in the above discussion, was made by Webber. He used the language of Veneziano's topological ( $1 / \mathrm{N}$ ) expansion (7), but I shall try to reproduce part of his argument in simpler terms. Let us look back at Section II where we introduced the twist operation. The effect of a twist was to change a quark into an antiquark and vice versa. Thus the twist acts as a charge conjugation operator. Consequently, the twisted and non-twisted diagrams contribute with opposite signs to the C even and C odd output trajectories. As a result the input f is promoted to become the Pomeron, but the input $\omega$ is "depromoted": $\alpha_{\omega}^{\text {out }}(0)<$ $\alpha_{\omega}^{\operatorname{in}}(0)$. In discussing the baryon exchange diagrams we implicitly assumed this same interpretation for twists. However, as Webber pointed out, there is a crucial difference between meson and baryon exchange diagrams: since a baryon twist simply interchanges quarks (rather than $Q$ and $\bar{Q}$ ) the twisted diagrams contribute with the same sign to both eigenstates of C and exchange degeneracy is preserved.


baryon twist

Webber suggests that the output fand $\omega$ trajectories are built up in all processes by baryon exchange diagrams. In $\mathrm{K}^{-} \mathrm{p}$ scattering, say, at low energies where the production of new $B \bar{B}$ pairs is unimportant, the relevant diagrams would be those where the baryon number propagates from the proton vertex to the $\mathrm{K}^{-}$vertex, as follows:


How should one evaluate the above suggestions? Firstly, it is easy to see that the classical solution 1 must be wrong since it provides us with many predictions which cannot be anything but nonsense. An example of such a prediction is that the $\Delta^{++} \bar{\Delta}^{-} \rightarrow$ pions cross section should be very small or vanish. (This is since the diagrams III and IV cannot contribute to this process.) To choose between the solutions 2 and 3 is more difficult. Although they are theoretically very different, they agree in many of their experimental predictions and it is not easy to find clear-cut tests to discriminate between them. It seems to me that the answer to the problem 'What builds up what in $\mathrm{B} \overline{\mathrm{B}}$ scattering?" will not follow in any straightforward way from experiment but requires improved theoretical understanding of the role quantum numbers play in the unitarity summation.

The duality diagrams, together with the quark diagram counting argument, provide predictions also for the multiplicity distributions. Within the framework of the oversimplified multiperipheral model discussed in Section II, one obtains the following simple prediction:

$$
\begin{equation*}
\langle n\rangle_{R}=\frac{1}{2}\langle n\rangle_{P}=\frac{1}{3}\langle n\rangle_{A} \text {, } \tag{10}
\end{equation*}
$$

where $<\mathrm{n}>_{\mathrm{i}}, \mathrm{i}=\mathrm{R}, \mathrm{P}, \mathrm{A}$, is the average multiplicity of the states that build up the Reggeon, Pomeron, and annihilation cross sections, respectively. This same prediction follows also from the more sophisticated framework of the topological expansion. Figure 4 shows a test of this prediction, taken from a recent paper by Dias de Deus (24). The agreement between data and the theoretical prediction is seen to be reasonably good.

Webber has formulated an explicit dual multiperipheral model for $\mathrm{B} \overline{\mathrm{B}}$ annihilation (25). Figure 5 shows the multiplicity distributions predicted by his model at 32,100 , and $200 \mathrm{GeV} / \mathrm{c}$, together with experimental data on the differences between $\mathrm{p} \overline{\mathrm{p}}$ and pp multiplicity distributions. Figure 6 shows a comparison between the model predictions and data on single pion inclusive distributions. The agreement is again impressive.

In an interesting contribution Chen et al. (26)


Fig. 4. Average charge multiplicity for Reggeon and annihilation components as a function of the Pomeron average multiplicity. (From Ref. 24.)


Fig. 5. Data on the differences between $\mathrm{p} \overline{\mathrm{p}}$ and pp charged multiplicity cross sections. The full curves show the fit to these data using the annihilation model of Webber. The dashed curve shows the model prediction for $200 \mathrm{GeV} / \mathrm{c}$. (From Ref. 25.)


Fig. 6. Annihilation model predictions of the $\pi^{+}$and $\pi^{-}$rapidity distributions, compared with data on pp annihilation at $12 \mathrm{GeV} / \mathrm{c}$. (From Ref. 25.)
present an analysis of data on the threebody annihilation reaction

$$
\mathrm{p} \overline{\mathrm{p}} \rightarrow \mathrm{~K}^{ \pm} \pi^{\mp} \mathrm{K}^{*}{ }^{\mathrm{O}} .
$$

They show that the qualitative features of the data contradict expectations based on baryon exchange models, but can be easily understood in terms of a more general quark diagram model. The results of this analysis are reviewed by Professor Fields (27).

In conclusion, let me emphasize that the most clear-cut prediction of duality dia- grams in $B \bar{B}$ scattering is the existence of exotic baryonium states. The experimental search of such states should be relentlessly pursued, both above and below the $N \bar{N}$ threshold.

## V. IS B $\overline{\mathrm{B}}$ ANNIHILATION CENTRAL OR PERIPHERAL?

A simple possibility, discussed in the previous section, is that the observed differences between $\mathrm{p} \bar{p}$ and pp interactions are solely due to the additional annihilation channels in $\mathrm{p} \overline{\mathrm{p}}$. This identification works well for the total cross sections and is also consistent with data on prong distributions (i.e., $\sigma_{\mathrm{n}}^{\text {annih }} \approx \sigma_{\mathrm{n}}(\mathrm{p} \overline{\mathrm{p}})-\sigma_{\mathrm{n}}(\mathrm{pp})$ ). One may then ask: Can one equate the difference between the $\mathrm{p} \overline{\mathrm{p}}$ and pp cross sections to the annihilation cross section at each impact parameter separately?

Let us first look at the b-space distribution of the total cross-section difference. This can be extracted from $p \bar{p}$ and pp elastic scattering data by solving the amplitudes in $t$ space and Fourier-Bessel transforming them to b-space. In order to do that, some assumptions of the behaviour of the phases of the amplitudes must be made.


Fig. 7. Impact parameter distribution of the $\mathrm{p} \overline{\mathrm{p}}$ and pp total crosssection difference at 50 and $175 \mathrm{GeV} / \mathrm{c}$. (From Ref. 28.)

Fortunately it turns out that the results are relatively insensitive to the assumptions made. Figure 7 shows the result of such an analysis, performed using the new high statistics Fermilab data of the Single Arm Spectrometer Collaboration (28). The cross-section difference is seen to be sharply peripheral, peaking around one Fermi. This result, namely that the total cross-section difference is peripheral, has been known for several years from analyses of lower energy data (see, e.g., Ref. 1). From Fig. 7 one sees that this feature of the data persists at high energies.

To compare the b-space distribution of the cross-section difference with that of the annihilation cross section, we must get some handle on the latter. To solve for $\sigma_{\text {annih }}{ }^{(b)}$ directly from data is clearly outside our present capabilities, since itwould require very detailed knowledge of the momentum space structure of the multiparticle amplitudes, including knowledge of their phases. Something, however, can be said. Webber has suggested a method of obtaining an experimental lower bound on the r.m.s. impact parameter of any exclusive process (29). This method is based on the uncertainty principle and works as follows: The impact parameter of a multiparticle amplitude is given by

$$
\begin{equation*}
\vec{b}=\sum_{i} x_{i} \vec{b}_{i} \tag{11}
\end{equation*}
$$

where the $x_{i}$ 's are the longitudinal momentum fractions and the $\vec{b}_{i}$ 's the impact parameters of the produced particles. Next, one defines a vector $\overrightarrow{\mathrm{p}}_{\perp}$,

$$
\begin{equation*}
\overrightarrow{\mathrm{p}}_{\perp}=\sum_{\mathrm{i}} \mathrm{u}_{\mathrm{i}} \overrightarrow{\mathrm{p}}_{L_{i}} \tag{12}
\end{equation*}
$$

where the $u_{i}$ 's are arbitrary functions of the longitudinal momentum fractions $x_{1}, \ldots$, $\mathrm{x}_{\mathrm{n}}$ and the $\vec{p}_{1}$ 's are the transverse momenta of the produced particles. It follows then from the ${ }^{1}$ uncertainty principle that

$$
\begin{equation*}
\left\langle b^{2}\right\rangle \geq \frac{\left(\sum_{i} u_{i} x_{i}\right)^{2}}{\left\langle p_{\perp}^{2}\right\rangle} . \tag{13}
\end{equation*}
$$

The right-hand side of Eq. (13) may now be maximized with respect to the quantities $u_{i}$. The maximum occurs when

$$
\begin{equation*}
x_{i}=\sum_{j} u_{j}\left\langle\vec{p}_{\perp_{i}} \cdot \vec{p}_{\perp_{j}}\right\rangle \tag{14}
\end{equation*}
$$

Solving Eq. (14) for the $u_{i}$ 's and substituting in Eq. (13) gives us a lower bound for the mean squared impact parameter of the collision.

The Liverpool-Stockholm Collaboration (30) has applied this method to their $\mathrm{p} \overline{\mathrm{p}}$ annihilation and non-annihilation data at 4.6 and $9.1 \mathrm{GeV} / \mathrm{c}$. They found the bound calculated from the annihilation sample ( $\mathrm{b}_{\mathrm{L}}=0.21 \pm 0.01 \mathrm{fm}$ at $9.1 \mathrm{GeV} / \mathrm{c}$ ) to be more central than that obtained for the non-annihilation events ( $\mathrm{b}_{\mathrm{L}}=0.31 \pm 0.02 \mathrm{fm}$ ). The
authors concluded that this lends support to the intuitive idea of annihilation processes being more central than the non-annihilation ones and that the simple identification of $\mathrm{p} \overline{\mathrm{p}}$ annihilation as making up the difference between the $\mathrm{p} \overline{\mathrm{p}}$ and pp interactions has to be abandoned.

The impact parameter method has been applied to various other processes by several collaborations ( $31-33$ ). Figure 8 shows the result for the bound $b_{L}$ in exclusive reactions of the form

$$
\pi^{-}+\mathrm{p} \rightarrow \mathrm{~N}+\pi^{\prime} \mathrm{s}
$$

at $16 \mathrm{GeV} / \mathrm{c}$. We see that the bound decreases with increasing multiplicity, in accord with the intuitive idea that higher multiplicity final states are produced on the average in more central collisions than the lower multiplicity ones.

Although I find the above analyses very interesting and worth pursuing further, I think that the following remark should be made. Looking at Fig. 8, we see that the values for $\mathrm{b}_{\mathrm{L}}$ vary between 0.15 and 0.5 fm . Hence they are considerably smaller than the average impact parameter <b> of all inelastic processes of $0.7-0.8 \mathrm{fm}$, known from the elastic scattering analysis. Consequently, the bound $\mathrm{b}_{\mathrm{L}}$ must be a rather weak one. It seems to me that until one understands the source of this weakness one should be careful not to draw any far-reaching conclusions from the behaviour of the bound.

The possibility of improving Webber's bound has been examined by Henyey and Pumplin (34), with promising results. Figure 9, which is taken from their paper, shows the result of a model calculation which suggests that, while Webber's bound may be a rather good one for central processes, it may badly underestimate the range of peripheral processes. Henyey and Pumplin propose several alternative bounds whose usefulness should be tested by experimental applications.
VI. NON-ANNIHILATION PROCESSES

Collisions which result in high transverse mo momentum secondaries have received much attention in the past few years (35). Experimental results on unexpectedly large particle yields at large angles and, in particular,
correlations between the particles produced at wide angles lend support to the hypothesis that hadrons are built up by point-like constituents and that, at high energies and large momentum transfers, the interaction between two hadrons can be regarded as a local interaction between their essentially free constituents. Theoretically, one expects the large angle spectra, particle ratios, correlations among particles produced in large $p_{t}$ events, etc., to show strong dependence on the valence quark structure of the colliding hadrons. Since a proton has only valence quarks and an antiproton has only valence antiquarks, comparison between antiproton-proton and proton-proton collisions should be a particularly effective method of probing the dynamics of the con-stituent-constituent scattering subprocess.


Fig. 10. The ratio between the pp and pp cross sections at $\cos \theta_{\mathrm{c}}$. m. $=0, \mathrm{R}_{0}$, as a function of the laboratory momentum. Also shown are the predictions of the parton interchange and the gluon exchange models. (From Ref. 36.)

In an interesting contribution to this Symposium, Carlson and Johansson (36) analyze data on $\overline{\mathrm{p}} \mathrm{p}$ and pp elastic scattering and on $\mathrm{p} p$ annihilation into $\pi \pi$ and $K \overline{\mathrm{~K}}$ and compare them with the predictions of the Constituent Interchange Model of Blankenbecler, Brodsky, and Gunion (37). Figure 10 shows data on the ratio of the pp and $\overline{\mathrm{p}}$ e elastic differential cross sections at $\theta_{\mathrm{c}} . \mathrm{m}=90^{\circ}$ vs the laboratory momentum of the beam particle. The CIM prediction for this quantity is $\approx 50$, whereas a naive model in which the partons scatter by exchanging a vector gluon predicts $R_{0} \approx 3.6$. The experimental situation is intriguing. Is the clustering of the data points around the gluon exchange model prediction at low energies an accident? (My guess is that this is so.) Does $\mathrm{R}_{0}$ increase with increasing energy as suggested by the three highest energy points and if it does, does it keep on increasing or level off at some constant value? Notice that all the data shown come from experiments at low energies, $\mathrm{p}_{\text {lab }} \leq 6.2 \mathrm{GeV} / \mathrm{c}$ : It would clearly be interesting to extend these measurements to higher energies, as well as to scan the transition region (?) between 4 and $6 \mathrm{GeV} / \mathrm{c}$.

Another interesting problem concerning nonannihilation $B \bar{B}$ reactions is the following. It has been known for some time that the cross sections of many antiproton-induced exclusive reactions are smaller than those of their proton-induced counterparts. A good example of this is provided by the processes

$$
\begin{equation*}
\overline{\mathrm{p}} \mathrm{n} \rightarrow \bar{\Delta}^{-\mathrm{p}} \tag{15}
\end{equation*}
$$

and

$$
\begin{equation*}
\mathrm{pp} \rightarrow \Delta^{++} \mathrm{n} \tag{16}
\end{equation*}
$$

The ratio of the cross sections of these processes appears to be independent of energy (38). Its numerical value is

$$
\begin{equation*}
\mathrm{R}=\frac{\sigma\left(\mathrm{pp} \rightarrow \Delta^{++} \mathrm{n}\right)}{\sigma\left(\overline{\mathrm{p} n} \rightarrow \bar{\Delta}^{--} \mathrm{p}\right)}=2.7 \pm 0.9 \tag{17}
\end{equation*}
$$

The currently accepted ideas of two-body scattering dynamics suggest the following description for the processes (15) and (16) (39). Both these processes are dominated by exchange of the pion pole in the t-channel of the scattering amplitude. The pole amplitudes are strongly modified by "absorption" corrections, which reduce their strengths at small impact parameters. Theoretically, one expects the strength of the absorptive corrections to be proportional to the total cross sections of the colliding particles. Since $\sigma_{\text {tot }}(\overline{\mathrm{p}})$ is larger than $\sigma_{\text {tot }}(\mathrm{pp})$, one is naturally led to expect the value of the ratio $R$ to be above one. But the experimental value for $R$ is so large that I find it hard to understand how any conventional absorption scheme would reproduce it. Furthermore, since the ratio of the $\bar{p} p$ and $p p$ total cross sections decreases rapidly with increasing energy, any conventional absorption prescription would predict $R$ to be strongly energy-dependent. Experimentally, however, the energy dependences of the processes (15) and (16) are really very similar (38): A fit of the form $\sigma \sim \mathrm{p}_{\text {lab }}^{-\mathrm{n}}$ in the $\mathrm{p}_{\text {lab }}$ range from 3 to $20 \mathrm{GeV} / \mathrm{c}$ yields the values $\mathrm{n}=2.1 \pm 0.1$ for the process (15) and $n=2.0 \pm 0.1$ for the process (16).

I think that the above problem deserves to be studied carefully. Experimental determination of the energy dependences of the density matrix elements of the processes (15) and (16) would be very valuable.

## VII. SUMMARY AND OUTLOOK

Let us try to list some crucial experiments that will throw light into our theoretical understanding of baryon-antibaryon interactions:

1. The search (and hopefully discovery!) of $Q Q \bar{Q} \bar{Q}$ "baryonium" states, both above and below the $\mathrm{N} \overline{\mathrm{N}}$ threshold
2. Comparison of the properties of baryon number annihilation and strangeness annihilation processes
3. Study of the multiparticle aspects of annihilation processes (correlations, etc.). Detailed comparison between annihilation and non-annihilation processes
4. Study of the isospin properties of $B \bar{B}$ annihilation by comparing $p \bar{p}$ and $n \bar{p}$ interactions. Since the differences are small, accurate experiments are needed.
5. Further development of the impact parameter analysis
6. Large angle scattering experiments, both exclusive and inclusive, over the widest possible energy range
7. Further two- and quasi two-body experiments with antiproton beams. Careful comparisons between $\mathrm{p} \overline{\mathrm{p}}$ and pp scattering. Studies of the differences in the strengths of the absorptive effects in pp and pp collisions.

When I returned home from our previous Symposium in Liblice two years ago, I felt slightly disturbed by the observation that our interests were so widely spread. Almost every participant seemed to be asking different questions, many of which bore no particular relationship to antiprotons but were problems common to all hadronic interactions. I felt (and I still feel) that, in order to be meaningful, a specialized Symposium should focus on those particular problems which are central to the field and in which important contributions can be made. Here in Stockholm I have been delighted by the observation that a number of important questions which can be best investigated using antiprotons have come up again and again. Let us now try to answer them. By doing that we are bound to gain a deeper understanding of how matter interacts with antimatter.

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