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INTERSECTING STORAGE ACCELERATOR NOTES

RESONANCE PHYSICS AT VERY HIGH ENERGIES

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Based on an invited talk presented 15 July to a study group for a new high-energy colliding beam facility at Brookhaven.

ABSTRACT

The following topics are discussed: diffraction, rarer final states, photon-photon processes, pionization, massive lepton pair production, and possible new types of resonances.

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1.

Introduction

Much of low-energy hadron physics is concerned with resonances.

At first glance the same does not seem to be true at high energy; in fact, it is just possible that the subject of the title is non-existent.

On the other hand, if resonances were an important part of physics at very high energies (say, above 20 GeV in the CM) they could be rather different from the meson and baryon states we know today. I shall speculate later on this latter possibility, which might prove quite exciting.

The complications of resonance physics at very high energies lie mainly in the tremendous number of particles produced. As the number of possible combinations increases, correlations become obscured in background. Missing-mass studies also become more difficult, as resolution functions generally broaden with increasing energy. For this reason even such studies as

$$p + p \rightarrow p + N^{*+}$$

(1)

may become extremely difficult at and above the energies of the CERN storage rings (ISR).

What, then, is to be gained in resonance physics by going to the highest available energy? One can think of several possibilities:

1. Some information on diffractive processes such as (1).
2. Study of decays into the rarer (heavier) final states, e.g. those involving $K\bar{K}$ or baryon-antibaryon pair production.
3. Use of high-energy (e.g. 15 GeV) colliding lepton beams as a source of photons to study the processes $\gamma \rightarrow \text{hadrons}$ or $\gamma\gamma \rightarrow \text{hadrons}$.
4. Resonances in the "plonization" region, if any.
5. Correlations in final lepton pairs.
6. New resonant effects unrelated to those at lower energies. If hadrons

were made of "partons", for example, such effects could involve excitation of the partons themselves, in the same manner that one would excite N^* resonances by nucleus-nucleus collisions.

Each topic will be discussed in turn.

1. Diffraction

An important question regards the choice of selection rules that tell which processes can involve Pomeranchukon exchange, thus approaching constant cross sections as energy increases. Such rules have been given by Gribov and Morrison,¹⁾ Chou and Yang,²⁾ Carlitz, Frautschi, and Zweig,³⁾ and more recently by Freund, Jones, and Rivers⁴⁾.

The Gribov-Morrison rule permits the Pomeranchukon to couple as if it were a 0^+ particle with arbitrary orbital momentum: hence $\pi(0^-) \rightarrow 1^+, 2^-, 3^+, \dots$ $1^G = 1^-$ while $\rho(1^-) \rightarrow 1^-, \{0^+, 1^+, 2^+\}$, $\{1^-, 2^-, 3^-\}, \dots, 1^G = 1^+$. (The latter is presumably relevant to a vector-dominance picture of the diffractively produced states in photoproduction). For baryons, $N(1/2^+, 1 = 1/2) \rightarrow 1/2^+, \{1/2^-, 3/2^-\}, \{3/2^+, 5/2^+\}, \dots$, $1 = 1/2$.

The Carlitz-Frautschi-Zweig rule³⁾ states that diffraction involves a "kick" given to one of the quarks in the particle which undergoes diffractive dissociation. This "kick" is assumed to change only the relative L of the quarks. In terms of $SU(3)$, the exchanged quantum numbers behave like an $SU(3)$ singlet. For example, $\pi(1^1S_0) \rightarrow A_1(3^3P_1)$ since the quarks change their spin state, while $\pi(1^1S_0) \rightarrow A_2(1^1D_2)$ is permitted. On the other hand, the quark spin conservation rule is treated as only approximate, so that a small constant contribution to $\pi \rightarrow A_1$ (and also to $\pi \rightarrow A_2$) is expected.

The Chou-Yang rules are similar to those of Ref. 3 in spirit, without committing themselves to a particular composite model of hadrons. One of

their selection rules implies that the forward cross section vanishes whenever the product of the parities of the particles A, B, C and D in $AB \rightarrow CD$ is negative. This rule was motivated by the absence of D_{13} production at small t in $pp \rightarrow pN^*$. On the other hand it would also predict a forward dip in $\pi N \rightarrow A_1 N$. Perhaps such an effect indeed occurs at higher energy.

Recently⁴⁾ it has been suggested that the Pomeron couples in every case for which the SU(3) singlet combination f_1 of the tensor mesons f and f' couples. Such a selection rule would allow the A_2 to be produced diffractively, for example. It is less restrictive than the rules mentioned above.

If particularly stringent rules govern the diffractive production of resonances at high energy, mass resolution may be less of a problem. The rules of ref. 3, for example, would lead to the survival of relatively few states at higher energy.

Even if individual resonances cannot be discerned at high energy in diffractive processes, one could certainly check the behaviour of charge multiplicities in the forward and backward directions. This would be particularly easy to do with colliding beams. A large contribution from diffractive processes would lead to a significant enhancement of events with an odd number of charged prongs in each hemisphere over corresponding even-even events. At present energies the large number of pions with small longitudinal momenta tends to obscure such correlations for high-multiplicity events, though they certainly hold in such lower-multiplicity reactions as $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$.⁵⁾

II Rarer final states

The production of kaons and baryon-antibaryon pairs in high-energy,

high-multiplicity reactions is rather rare, most probably as a result of the strong dependence of the production mechanism on the mass of the particle produced⁶⁾. Moreover, pairs of such particles might tend to be correlated with one another more strongly than would pion pairs.

An ideal setup would then be to study such events as

$$pp \rightarrow pp K_1^0 K_1^0 (m\pi) , \quad (2)$$

$$pp \rightarrow pp K^+ K^- (m\pi) , \quad (3)$$

or

$$pp \rightarrow pp p\bar{p} (m\pi) . \quad (4)$$

The first of these might be done using some rudimentary V-recognition trigger which would not exclude the presence of additional charged pions (these would almost certainly be present). The latter could be done using Cerenkov triggers. One would be interested in the mass of the rare pairs themselves, but also in masses which included other charged particles - such as $M(K_1^0 K_1^0 \pi^\pm)$, for example.

III. Uses of Lepton Beams

The question of whether appreciable resonance production occurs in $e^+e^- \rightarrow \text{virtual } \gamma \rightarrow \text{hadrons}$ will certainly be answered at lower energies within the next year or two. Going to higher energies in such a process may not help much if the total cross section for hadron production has the $1/E^2$ behaviour characteristic of a pointlike interaction. On the other hand, at high energies, such a reaction would be one of the sure ways of producing pairs of very massive charged particles.

A process more highly dependent on increased lepton energy is the two-photon one recently discussed by Brodsky, Kinoshita, and Terazawa⁷⁾.

$$e^+e^- \rightarrow e^+e^- + \text{hadrons} \quad (5)$$

in which each lepton acts as the source of a photon close to its mass shell, the two photons then combining to form hadrons. The cross section for such a process rises logarithmically with energy: specifically,

$$\sigma(ee \rightarrow ee + \text{hadrons}) = 2 \left(\frac{\alpha}{\pi} \ln \frac{E}{m_e} \right)^2 \int_{4m_\pi^2}^{4E^2} \frac{ds}{s} f\left(\frac{\sqrt{s}}{2E}\right) \sigma_{\gamma\gamma \rightarrow h}(s), \quad (6)$$

where E is the energy of each beam, $\sigma_{\gamma\gamma \rightarrow h}(s)$ is the cross section for production of hadrons by two unpolarized photons with total CM energy $\sqrt{s}$, and

$$f(x) = (2 + x^2)^2 \ln \frac{1}{x} - (3 + x^2)(1 - x^2) \quad (7)$$

A question of interest here is the fraction of $\sigma_{\gamma\gamma \rightarrow h}(s)$ which can be expected to be due to resonances. This turns out to be easily estimated using some elementary ideas of duality and factorization. We neglect the possibility of fixed poles in what follows and adopt the conventional Regge pole model for total cross sections, whereby $\sigma_{\gamma\gamma \rightarrow h}(s)$ is given by a constant (Pomeranchuk) part plus a part decreasing with increasing s due to the leading non-Pomeranchuk trajectories: in this case, the f and A_2 .

One then writes:

$$\sigma_{\gamma\gamma \rightarrow h}(s) = \sigma_0 + \sigma_1/s^{1/2} \quad (8)$$

bearing in mind that the intercepts of the f and A_2 are roughly $1/2$. The use of duality comes in ascribing the non-Pomeranchuk trajectory exchange to the average effects of direct channel resonances⁹⁾. Even if such resonances could not be separated from one another without a detailed study of the hadronic final state, observation of a falling part in $\sigma_{\gamma\gamma \rightarrow h}(s)$ ($\sigma_1 \neq 0$) would be strong evidence for their presence.

One can test the predictions of factorizability for the Pomeranchuk

trajectory by comparing the experimental value of σ_0 with that predicted by

$$\sigma_0 = \frac{[\sigma_T^{S=\infty}(\gamma N)]^2}{\sigma_T^{S=\infty}(NN)} \quad (9)$$

Using $\sigma_T^{S=\infty}(\gamma N) = 95 \mu b^{10}$ and $\sigma_T^{S=\infty}(NN) = 37 mb$ (see sec. VI, below) one predicts

$$\sigma_0 = 0.24 \mu b \quad (10)$$

To estimate σ_1 one can make a table,¹¹⁾ based on exchange degeneracy, of couplings of the various non-Pomeranchuk trajectories to p, n, and γ :

	<u>Trajectory</u>	<u>f</u>	<u>A₂</u>	<u>ω</u>	<u>ρ</u>
<u>Particle</u>					
p		a	b	a	b
n		a	-b	a	-b
γ		c	d	o	o

The entries in this table imply the following non-Pomeranchuk contributions to total cross sections. Let us define

$$\Delta(AB) = \sigma_T(AB) - \sigma_T^{S=\infty}(AB) \quad (11)$$

Then

$$s^{1/2} \Delta(\bar{p}p) = 2(a^2 + b^2) \quad (12a)$$

$$s^{1/2} \Delta(\bar{p}n) = 2(a^2 - b^2) \quad (12b)$$

$$s^{1/2} \Delta(\gamma p) = ac + bd \quad (12c)$$

$$s^{1/2} \Delta(\gamma n) = ac - bd \quad (12d)$$

$$\sigma_1 = s^{1/2} \Delta(\gamma\gamma) = c^2 + d^2 \quad (12e)$$

The first four numbers are known, allowing one (in principle) to solve for a, b, c and d and thus to obtain σ_1 . In practice, however, b^2 is so small

and so poorly known that one cannot obtain d in a satisfactory way from eqs. (12a - 12d). Instead, by using the assignments

$$\gamma \sim \begin{vmatrix} 2/3 & & \\ & -1/3 & \\ & & -1/3 \end{vmatrix} \begin{Bmatrix} f_0 \\ A_2 \end{Bmatrix} = \frac{1}{\sqrt{2}} \begin{vmatrix} 1 \\ \pm 1 \\ 0 \end{vmatrix} \quad (13)$$

and the SU(3) - invariant coupling $\text{Tr}(\gamma\gamma T)$ (where T stands for f_0 or A_2) one finds¹²⁾

$$\frac{d}{c} = \frac{g(\gamma\gamma A_2)}{g(\gamma\gamma f_0)} = \frac{3}{5} \quad (14)$$

Since $b^2 \ll a^2$ one can write $2a^2 \approx s^{1/2} \Delta(\bar{p}p)$, so that

$$c^2 = [s^{1/2} \Delta(\gamma p) + s^{1/2} \Delta(\gamma n)]^2 / 2 s^{1/2} \Delta(\bar{p}p) \quad (15)$$

Using

$$s^{1/2} \Delta(\bar{p}p) = 67 \text{ mb (see VI, below)} \quad (16a)$$

$$s^{1/2} \Delta(\gamma p) = 92 \text{ } \mu\text{b, }^{13)} \quad (16b)$$

$$\text{and } s^{1/2} \Delta(\gamma n) = 71 \text{ } \mu\text{b, }^{13)} \quad (16c)$$

with s in GeV^2 , one then finds

$$\sigma_1 = 0.27 \mu\text{b} \quad (17)$$

In (16a) we have neglected the fact that $\sigma_T(pp)$ falls slightly, which could modify our exchange-degenerate argument by a small amount if not due to (say) Regge cuts.

To summarize, then, factorization for both Pomeranchukon and non-Pomeranchukon exchanges in $\sigma_T(NN)$ and $\sigma_T(\gamma N)$ predicts

$$\sigma_T(\gamma\gamma) = 0.24 + 0.27/s^{1/2} \text{ } \mu\text{b,} \quad (18)$$

allowing one to estimate the relative fraction of background (first term in (18)) and resonances (second term in (18)). An additional small resonant

contribution (of the order of a few percent of the second term in (18)) could be expected to come from the neglected f' trajectory. It would manifest itself in the form of $C = +$ resonances forbidden by the quark model to decay to systems without at least one kaon pair.

Comparing the first and second terms of (18) at various energies, then, one finds the following average ratios of resonances to background for the energy ranges indicated:

<u>Range of $s^{1/2}$, GeV</u>	<u>Resonances/Background</u>
.3 to 1	2 to 1
1 to 2	1 to 1
2 to 6	1 to 3
6 to 30	1 to 5

Even at fairly high energies, these are not particularly bad values if the resonances turned out to be distinct from one another. If one concentrates on specific final states, this may indeed be the case. For example, including all the states in the quark model for $q\bar{q}$, $L \leq 3$, one has the following resonances for two and three-pion states¹⁴⁾

<u>Final State</u>	<u>Name</u>	<u>Mass</u>	<u>$2S+1$ $L_J(q\bar{q})$</u>	<u>$1^{G_J P}$</u>
$\pi^+ \pi^-$	ϵ or σ	750	3P_0	$0^+ 0^+$
	f_0	1260	3P_2	$0^+ 2^+$
	$[\epsilon^*]$	1600 to 1800	3F_2	$0^+ 2^+$
	$[f_0^*]$	1900	3F_4	$0^+ 4^+$

(cont'd)

$\pi^+ \pi^- \pi^0$	η	550	$1s_0$	$0^+ 0^-$
	A_2	1300	$3p_2$	$1^- 2^+$
	π_A	1650	$1d_2$	$1^- 2^-$
	$[\delta^*]$	1700 to 1800	$3F_2$	$1^- 2^+$
	$[A_1^*]$	1800	$3F_3$	$1^- 3^+$
	$[A_2^*]$	1900	$3F_4$	$1^- 4^+$

The $K^+ K^-$ final state will exhibit all of the above resonances with natural J^P (as well as the S^* and f' and their recurrences) and may be more complicated. However, it does afford a particularly clean way of studying $f_0 - A_2$ interference and comparing it with SU(3) predictions. If one defines both f_0 and A_2 amplitudes to $K^+ K^-$ as real and positive, then SU(3) predicts the decay amplitudes to be equal and the production amplitudes to be in the ratio of $5(f_0)$ to $3(A_2)$.

Eq. (18) implies the following values for $\sigma_{ee \rightarrow ee + \text{hadron}}$ (Eq. (6)) at $E = 3$ and $E = 15$ GeV when slices of $\sqrt{s}$ are taken:

	$E = 3$	$E = 15$
Range of $\sqrt{s}$, GeV		
.3 to 1	11 nb	30 nb
1 to 2	1.7 nb	6.9 nb
2 to 6	.6 nb	5.1 nb
6 to 30	-	1.8 nb

Eq. (19) shows the following:

1) It does not pay to increase the beam energy from 3 to 15 GeV in order to study the region below $\sqrt{s} = 1$ GeV (e.g., the ϵ or η'), as the cross section is already appreciable at the lower energy and does not increase significantly.

2) For higher s one begins to need larger E in order to take advantage

of the sharp peaking of $f(x)$ (Eq. (7)) for small x .

3) There is still appreciable cross section expected beyond $\sqrt{s} = 6$ GeV for $E = 15$ GeV.

A note should be added about the problem of center-of-mass motion, which turns out not to be as acute as I had expected. The two-photon system is not at rest but has a distribution in P , the 3-momentum along the beam axis, proportional to

$$W(P, s, E) = \frac{1 + (1 - P/E)^2}{s \sqrt{s} + P^2} \quad (20)$$

for very small $\sqrt{s}/2E$. Hence, aside from the slowly varying factor in the numerator, $W(P, s, E)$ does not depend on E when $E \gg \sqrt{s}$, but is cut off as $1/P$ for $P \gg \sqrt{s}$. This "limiting distribution" implies that the laboratory angular distributions in such processes as $\gamma\gamma \rightarrow e \rightarrow \pi^+ \pi^-$ will not look too different when one passes from $E = 3$ to $E = 15$ GeV; CM motion will not prevent one from studying low-mass systems with high energy colliding lepton beams.

IV. Resonances in the "pionization region", if any

There may be no "pionization region", and there may be no resonances in such a region even if it were to exist. However, both questions are particularly easy to study in a colliding-beam experiment. Included in this category is the test for double-Pomeranchukon exchange proposed by Wilson¹⁵⁾. One looks for the e travelling slowly in the CM in

$$pp \rightarrow pp \quad \begin{array}{c} e \\ \downarrow \\ \pi^+ \pi^- \end{array} \quad (21)$$

This process does not yet seem to have become important in the similar pion-induced reaction at 25 GeV/c¹⁶⁾.

An interesting effect of multi-particle systems has been noted by Erwin¹⁷⁾. If one plots such mass spectra as $M\{(6\pi)^0\}$ or $M\{(6\pi)^{--}\}$ from high multiplicity $p\bar{p}$ events at 25 GeV/c one sees the usual phase-space distribution plus an accumulation of combinations with mass around 1600 MeV. It turns out that this effect can be ascribed to several events in which more than six pions are slow in the CM, giving rise to many low-mass six-pion combinations. Whether a resonant behaviour or not, such events demonstrate the general importance of mass spectra for discovering interesting correlations.

V. Correlations in final lepton pairs

A colliding-beam geometry is particularly suitable for the study of such reactions as

$$p + p \rightarrow \mu^+ + \mu^- + \text{anything} \quad (22)$$

which can be expected to involve large momentum transfers to the $\mu^+\mu^-$ system. In a reaction giving indirect information about (22), namely $p + U^{238} \rightarrow \mu^+ + \mu^- + \dots$,¹⁸⁾ the region $m_{\mu\mu} \leq 6$ GeV has been explored, with no conclusive evidence for any resonances decaying to $\mu^+\mu^-$. In principle such a system would be able to detect the presence of any neutral $J = 1$ boson with a direct coupling to photons.

It is of interest to review briefly the discussion of the process (22) based on parton models¹⁹⁾. Let the two protons have momenta P_1 and P_2 , respectively. The "parton-annihilation" picture¹⁹⁾ assumes that the muon pair is generated via a virtual photon by the annihilation of a parton in the first proton with momentum $x_1 P_1$ with an antiparton in the second proton of momentum $x_2 P_2$. The mass of the dimuon system is then

$$m_{\mu\mu}^2 \equiv Q^2 = (x_1 P_1 + x_2 P_2)^2 = x_1 x_2 s, \quad (23)$$

where s is the square of the total CM energy. (A formal passage to an infinite-momentum frame must be made to guarantee the validity of the impulse approximation used above).

The differential cross section with respect to Q^2 for the process (22) may then be related to structure functions like those involved in deep inelastic electron scattering on nucleons¹⁹⁾

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3(Q^2)^2} \mathcal{F}(\tau) \quad (24)$$

$$\text{Where } \mathcal{F}(\tau) \equiv \int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1 x_2 - \tau) \sum_a \frac{F_{2a}(x_1) F_{2\bar{a}}(x_2)}{\lambda_a^2} \quad (25)$$

$$\text{and } \tau \equiv Q^2/s \quad (26)$$

$F_{2a}(x_1)$ is $x_1 \lambda_a^2$ times the probability of finding a parton of type a in the first proton with momentum fraction x_1 , while $F_{2\bar{a}}(x_2)$ is a similar function for antipartons in the second proton. The appearance of the product $F_{2a} F_{2\bar{a}}$ means that one must divide out by the square of the parton charge, λ_a^2 , since each function already contains this quantity. For deep inelastic electron scattering, $W_2 = \sum_a F_{2a}$ in the scaling limit.

It has been suggested that F_{2a} and $F_{2\bar{a}}$ have similar behaviour.¹⁹⁾ One can in fact undo the convolution in (25) very simply to test this. The momentum transfer to the dimuon system is given in the scaling limit by

$$\begin{aligned} t &\equiv (Q - P_1)^2 \\ &= Q^2 - 2 P_1 \cdot (x_1 P_1 + x_2 P_2) \\ &= Q^2 - x_2 s \end{aligned} \quad (27)$$

so that a knowledge of $\tau = Q^2/s$ and t/s uniquely specifies x_1 and x_2 :

$$x_1 = [1 - t/Q^2]^{-1} \quad (28)$$

$$x_2 = (Q^2 - t)/s \quad (29)$$

Then

$$(Q^2 - t) (Q^2)^2 \frac{d^2 \sigma}{dQ^2 dt} = \frac{4\pi\alpha^2}{3} \sum_a \frac{F_{2a}(x_1) F_{2\bar{a}}(x_2)}{\lambda_a^2} \quad (30)$$

The quantity on the left hand side, plotted as a function of x_1 and x_2 , should be symmetric under $x_1 \leftrightarrow x_2$ if F_{2a} and $F_{2\bar{a}}$ are indeed the same.

In an orthodox three-quark picture of protons, $F_{2\bar{a}}$ would be zero for pp collisions, but equal to F_{2a} for $p\bar{p}$ collisions. It might then be of particular interest to study colliding $p\bar{p}$ reactions²⁰⁾, as has been suggested for the proposed AGS storage rings. Unfortunately flux limitations might make this particularly difficult; an exploratory experiment such as $\bar{p} + U^{238} \rightarrow \mu^+ + \mu^- + \dots$ should certainly be done first to establish an order of magnitude for the $p\bar{p}$ process. Because of the possibility that pions possess more antipartons than protons, a reaction like $\pi^- + U^{238} \rightarrow \mu^+ + \mu^- + \dots$ would also be of great interest.

One should point out that other models for the process (22), such as that of ref. (20), may not possess the scaling behaviour implicit in Eqs. (24) - (26) and (30).

Let us suppose for the sake of discussion that a parton and anti-parton form a strong vector meson resonance at some high mass. Clearly the scaling behaviour in (24) will then appear to break down, with a bump in $\hat{F}(\tau)$ moving toward low τ as s increases. On the other hand, the presence of many such resonances may not be incompatible with scaling behaviour, as has been suggested for the analogous case of deep inelastic electron scattering²²⁾.

For transversely polarized virtual photons, one expects an angular distribution in the dimuon CM of the form $1 + \cos^2 \theta^*$, where θ is the angle made by one of the muons with the direction defining the photon polarization. For longitudinal photons, this distribution is $\sin^2 \theta^*$.²³⁾ This distribution is of interest in testing parton models;¹⁹⁾ furthermore a change in the distribution as $m_{\mu\mu}$ is varied can help separate out resonant effects from a rather rapidly varying¹⁸⁾ background.

In the data of ref. 18; the corrected values of $d\sigma/dm_{\mu\mu}$ do show a broad structure around 3.5 GeV. However, the systematic errors of the experiment are not well enough known to allow identification of this structure as a resonance. (It does not appear in the raw data). Studies of t and θ^* distributions of such an effect, if it is found to persist, would be helpful.

To summarize the main points of this section, experiments such as the production of very massive muon pairs in hadron-induced reactions¹⁸⁾ should be carried out for a range of t as well as s and Q^2 , with incident antiprotons as well as protons, and with acceptance suitable for measuring θ^* distributions.

IV. New Resonant Effects.

Suppose hadron physics at present energies bears some relation to nuclear physics in the several MeV range. Hadron A (nucleus A) and hadron B (nucleus B) collide and form either a compound hadron C (nucleus C) or a state in which one or both hadrons (nuclei) are excited.

In the specific case of $n - C^{12}$ scattering, for example, the total cross section is known from a neutron kinetic energy T_n of zero up to several tens of GeV¹⁴⁻²⁷⁾. Below $T_n = 100$ keV $\sigma_T(nC)$ appears to be roughly constant in the 4 to 5 barn range. It then begins to decrease,

with the first prominent resonance appearing around 2 MeV corresponding to the first excitation of the compound nucleus C^{13} . Many such bumps appear in the total cross section thereafter, with the general trend downward to an average of 1 barn at 10 MeV. A prominent rise is then associated with the onset of inelastic processes (such as $C^{12}(n,n')3\alpha$) above 10 MeV: the cross section rises by $\sim 1/2$ barn in the 10-20 MeV range. $\sigma_T(nc)$ then falls smoothly to about 280 mb at $T_n = 300$ MeV. This falling behaviour is also characteristic of nucleon-nucleon scattering, indicating that the neutron is now seeing C^{12} as a collection of individual nucleons. The cross section then rises to a value of about 360 mb at 1.5 GeV, after which it decreases gradually again. This last rise is of particular interest since it probably reflects the excitation of N^* resonances or, at least, the onset of pion production (which leads to a similar peak in $\sigma_T(pp)$).

Every phenomenon but the last has been identified in hadron physics, as shown in Table 1. The last process would correspond to excitation of individual "bits" in the hadron or to inelastic processes taking place off the individual "bits".

Another example of a nuclear process whose analogue in hadron physics is as yet unknown is the absorption of a pion by a nucleon in a nucleus to form the (3,3) resonance. This gives rise to peaks in $\sigma_T(\pi A)$,²⁸⁾ occurring for pion kinetic energies similar to (but slightly lower²⁹⁾ than) that associated with (3,3) resonance formation on free nucleons. Correspondingly, one might expect the "bits" in one hadron to form resonances with the "bits" of the other hadron for sufficiently high relative momentum of the "bits".

We would like to suggest that the rise in $\sigma_T(K^+p)$ recently reported in the 20-55 GeV range³⁰⁾ may be related to one of the above effects:

Structure in $\sigma_T(nC)$	Energy Range	Interpretation	Structure in hadron σ_T	Energy Range	Interpretation
Constant	$T_n \leq 100$ keV	Scattering length	Constant $\sigma_T(K^+p)$	$T_K \leq 400$ MeV	Scattering length
Pronounced bumps; falling trend	1 - 10 MeV	Compound nucleus resonances	Bumps in $\sigma_T(\pi N)$	200 MeV to 2 GeV	Direct Channel resonances (DCR)
Rise	10 - 20 MeV	Inelastic Channels	Rise in $\sigma_T(pp)$	Peak at 1 GeV	Onset of pion production or N^* excitation
Falling trend	20 - 300 MeV	$\sigma_T(NN)$ falls	$\sigma_T(AB)$ falls when AB non-exotic	2 to 25 GeV	Duality or falling $\sigma_T(q_i q_i)$
Rise	300-1500 MeV	Onset of pion production or N^* excitation	?		

TABLE 1 - Correspondence between nuclear and hadronic total cross sections. All energies are lab. kinetic energies

either to excitation of partons by one another to resonant states, or to formation of resonances between partons in the target and beam particles.

In either case the conventional Regge language of (poles + cuts), while capable of fitting the data,³¹⁾ may not be the simplest way of viewing such phenomena.

It has been argued^{19) 32)} that partons bearing a finite fraction of the momentum of a hadron are not expected to play an important role in purely hadronic reactions. Our suggestion will imply that, while this may be true for hadron physics at lower energies, the structures in σ_T measured at Serpukhov may in fact be telling us about such "fast" partons. We shall thus discuss only a quantity $\Delta\sigma$, which is the deviation of σ from the value which may be understood via simple Regge poles. This simple Regge pole language we take to be associated with the "wee" partons.

Fits to total cross sections on hydrogen of the form $\sigma_T = \sigma_0 + \sigma_1 p_L^{-1/2}$ are illustrated in Fig. 1. These fits are made by eye, with the constraint that $\sigma_T(XY) = \sigma_T(\bar{X}Y)$ at $p_L = \infty$, and that the fit need be good only in the region of relatively low energy ($6 \leq p_L \leq 20$ GeV/c). Such fits involve exchange of Regge trajectories of the vector and tensor mesons [$\alpha(0) = 1/2$] and of the Pomeranchukon [$\alpha(0) = 1$]³³⁾.

There appear marked deviations $\Delta\sigma$ from the fits at higher energies in all cases except the pp and $\bar{p}p$ ones.³⁴⁾ These deviations are hard to understand on the basis of multiple-Pomeranchukon exchange, since the strength of the associated Regge cuts must then be taken much less in pp than in Kp or πp scattering³¹⁾. One would have expected the reverse situation a priori.

The fact that the deviations $\Delta\sigma$ are more marked in MB than in BB reactions

at similar p_L suggests that parton ideas may be of some use. In the most naive sense if $\Delta\sigma$ arises from a threshold effect for interaction of various "bits" of matter with one another, it is the "momentum per bit" which matters.

One can guess that $\sigma_T^\infty(MB)/\sigma_T^\infty(BB)$ is roughly proportional to the ratio of numbers of "bits" of the beam particles. (The superscript denotes infinite energy). Then p_L/σ_T^∞ is a rough measure of the "momentum per bit". In Fig. 2 we have plotted $\Delta\sigma$ against p_L/σ_T^∞ for πN , KN , and NN . One sees some hint of a universal structure for the meson-baryon reactions, while in the baryon-baryon case the energy is not yet large enough to see this structure. Structure should certainly be apparent at NAL, however.

Entirely similar conclusions hold for total cross sections on deuterium (Figs. 3, 4). In an attempt to be more quantitative one can introduce momentum distributions of partons as in the previous section:

$$\Delta\sigma = \int_{Q_{min}^2}^s dQ^2 \sum_{aa'} \sigma_T^{aa'}(Q^2) \int_0^1 dx_1 P_a(x_1) \int_0^1 dx_2 P_{a'}(x_2) \delta(Q^2 - x_1 x_2 s) \quad (31)$$

where $\sigma_T^{aa'}(Q^2)$ expresses the total cross section for direct parton-parton interaction, and the distribution function $P_a(x)$ expresses the probability of finding parton a with a fraction x of the total hadron momentum. For the specific case of $\mu^+\mu^-$ pair production, Eq. (31) reduces to Eqs. (24)-(26).

Typical cases for $\sigma_T^{aa'}(Q^2)$ might include the following:

$$\begin{aligned} (a) \quad \sigma_T^{q\bar{q}}(Q^2) &= \sigma_0 \delta(Q^2 - Q_0^2) \\ \sigma_T^{qq}(Q^2) &= 0 \end{aligned} \quad (32)$$

$$\begin{aligned}
 (b) \quad \sigma_T^{qq}(Q^2) &= \sigma_0 \delta(Q^2 - Q_0^2) \\
 \sigma_T^{q\bar{q}}(Q^2) &= 0
 \end{aligned}
 \tag{33}$$

$$(c) \quad \sigma_T^{qq}(Q^2) = \sigma_T^{q\bar{q}}(Q^2) = \sigma_0 \delta(Q^2 - Q_0^2)
 \tag{34}$$

$$(d) \quad \sigma_T^{qq}(Q^2) = \sigma_T^{q\bar{q}}(Q^2) = \sigma_0 \theta(Q^2 - Q_0^2)
 \tag{35}$$

Case (a) corresponds to formation of a resonance at Q_0^2 between any quark and any antiquark. It would lead to a rise in $\sigma_T(\text{MB})$ and - at a higher momentum - $\sigma_T(\bar{\text{B}}\text{B})$, but not in $\sigma_T(\text{B}\text{B})$.³⁵⁾ The rise in $\sigma_T(\bar{\text{B}}\text{B})$ should be three times that in $\sigma_T(\text{MB})$.

Case (b) corresponds to formation of a resonance at Q_0^2 between any pair of quarks. $\sigma_T(\text{B}\text{B})$ would show the rise, not $\sigma_T(\bar{\text{B}}\text{B})$. Again, it should be three times that in $\sigma_T(\text{MB})$.

Cases (c) and (d) treat quarks and antiquarks equivalently. In contrast to the previous two cases, they would not lead to anomalies in the difference between $\sigma_T(\bar{\text{B}}\text{B})$ and $\sigma_T(\text{B}\text{B})$. Both of these total cross sections should show a $\Delta\sigma$ of roughly 3/2 that in $\sigma_T(\text{MB})$.

Case (d) corresponds most closely to that discussed at the beginning of this section (N^* excitation in C^{12} by neutrons). In the present example, it would involve an excitation process with a threshold somewhere above $Q^2 = 10 \text{ GeV}^2$.

The use of realistic structure functions in Eq. (31) is hampered by our total ignorance of $P_a(x)$ for mesons. It is amusing, however, to make a general remark based on the parton models discussed by Bjorken and Paschos³⁶⁾. An N-particle composite with a longitudinal phase space distribution for all partons has

$$P_a^N(x) = (N-1)(1-x)^{N-2} \quad (36)$$

so that for $\sigma^{aa'}(Q^2) \sim \delta(Q^2 - Q_0^2)$ or $\theta(Q^2 - Q_0^2)$, the threshold behaviour of $\Delta\sigma$ is

$$\Delta\sigma \sim (1 - \tau_0)^{N_1 + N_2 - 3} \quad (\tau_0 \equiv \frac{Q_0^2}{s} \rightarrow 1) \quad (37)$$

when the two hadrons have N_1 and N_2 partons, respectively. The larger N_1 , the more slowly $\Delta\sigma$ would begin to rise as s/Q_0^2 rose above 1.

The behaviour

$$P_a(x) \sim (1-x)^p \quad (x \rightarrow 1) \quad (38)$$

has been related^{22,37)} to that of the elastic form factors:

$$G(q^2) \sim (q^2)^{-(p+1)/2} \quad (|q^2| \rightarrow \infty) \quad (39)$$

where $p = 3$ is suggested by the proton data²²⁾. Taking seriously the suggestion that p in Eq. (38) is larger for a more highly composite system³⁶⁾ (see Eq. (36)) one would guess $p = 0$ to 2 for mesons. Then as $\tau_0 \equiv s/Q_0^2 \rightarrow 1$ one might have

$$\Delta\sigma^{MB} \sim (1 - \tau_0)^4 \text{ to } 6 \quad (40)$$

$$\Delta\sigma^{BB} \sim (1 - \tau_0)^7 \quad (41)$$

Note that these powers (except for $p = 0$ in the meson case) are inconsistent with naive parton pictures of mesons as $q\bar{q}$ and baryons as qqq . In any case, effects in $\sigma_T^{(BB)}$ or $\sigma_T^{(\bar{B}\bar{B})}$ would be slower in getting started, as s increased above Q_0^2 , than corresponding effects in $\sigma_T^{(MB)}$.

If we take case (c) or (d) and use $N = 2$ for mesons and $N = 3$ for baryons in Eq. (36), we find the values of $\Delta\sigma$ indicated in Figs. 5 and 6. These results indicate that while $\Delta\sigma$ (MB) rises earlier than $\Delta\sigma$ (BB), these effects are not too dissimilar at higher energies. The fact that

$\Delta\sigma(BB)$ appears at present to be so small in comparison with $\Delta\sigma(HB)$ then indicates that the meson and baryon structure functions are much less similar than in such a naive picture (the baryon structure function is certainly not correct), that the fits are oversimplified³⁸⁾, or that the Serpukhov effects are just the beginning of much more spectacular behaviour. In the latter case, however, one might begin to worry about the safety of dispersion relations. One might hope for some independent information about meson structure functions from comparing massive $\mu^+\mu^-$ pair production using pion and proton beams (see V, above).

The trouble with the above picture is mainly that it is not at all a necessary one at present. The replacement of the Pomeranchuk pole by a pole plus cuts seems almost inevitable from many experimental and theoretical standpoints. It is somewhat hard to understand the weakness of such an effect (which would make σ_T rise) in $\sigma_T(pp)$ as compared with $\sigma_T(K^+p)$, but perhaps predictions of this fact already exist, and if not, they will certainly be made. The present approach may be somewhat more compelling - as cases (a) and (b) above illustrate - if $\sigma_T(\bar{p}p) - \sigma_T(pp)$ behaves wildly at higher energies.

A relation between our approach and conventional Regge phenomenology can be made for case (d) ("parton excitation") in that such a process can occur very easily without any quantum numbers being exchanged. One might then describe all of what we suggest in terms of some complicated J-plane structure for the Pomeranchukon. Even the scaling of momenta for meson versus baryon beams can be motivated in such a context, for example in the multiperipheral model.³⁹⁾ Moreover, an intimate connection exists between Regge cuts and compositeness. It is therefore not clear whether a "resonance" language would be needed at all. However, the presence of

unusual structure in total cross sections at higher energies would in any case be only the first step toward seeing whether some new form of "resonance physics" were present. One might try to correlate the rises in σ_T with the onset of some new types of events: for example, ones with especially large transverse hadron momenta. New structures in $d\sigma/dt$ might also begin to appear. One can only hope that if

new resonant effects appear at the energies available to the new machines, they will be rich enough to give us some new clues as to how matter behaves at very small distances.

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FIGURE CAPTIONS

Fig. 1. Fits to total cross sections on hydrogen of (a) pions, (b) kaons, (c) protons and antiprotons. The numbers shown are in mb; p_L is in GeV/c. These fits are in substantial agreement with those of Ref. 31, which give

$$\begin{aligned}\pi^- p &= 21.3 + 17.6 E_L^{-1/2}, \quad \pi^+ p = 21.3 + 11.2 E_L^{-1/2}, \\ K^- p &= 17.1 + 17.1 E_L^{-1/2}, \quad K^- n = 17.1 + 11.45 E_L^{-1/2}, \\ K^+ n &= K^+ p = 17.1, \quad \bar{p} p = 37.4 + 50.7 E_L^{-1/2}, \quad p p = 37.4 + 7.4 E_L^{-1/2}.\end{aligned}$$

Our coefficient of $p_L^{-1/2}$ is slightly low as a result of a plotting error, but this does not affect the results substantially.

Fig. 2. Deviations $\Delta\sigma$ from the fits of Fig. 1 plotted against p_L/σ_T^∞ , which is a rough relative measure of the "momentum per parton" in the beam particle. The momentum in the pp and $\bar{p}p$ cases is apparently too small to see the deviations present in πp and Kp .

Fig. 3. Fits, similar to those of Fig. 1, to total cross sections on deuterium of (a) pions, (b) kaons, (c) protons and antiprotons.

Fig. 4. Deviations $\Delta\sigma$ from the fits of Fig. 3 plotted against p_L/σ_T^∞ .

Note:- In Figs. 1-4 the circles represent Serpukhov data presented at Kiev (negative beam particles) or Amsterdam (positive beam particles; see Ref. 30); the inverted triangles represent older Serpukhov data (Ref. 40); while the squares represent the data of Ref. 41 (pions) Ref. 42 (protons), or Ref. 43 (other beam particles).

Fig. 5. Predicted total cross section contribution $\Delta\sigma$ due to a parton-parton interaction of the form $\sigma^{aa'}(Q^2) = \sigma_0 \delta(Q^2 - Q_0^2)$ (independent of a and a'). The contribution is shown in units of σ_0/Q_0^2 .

for (a) meson-baryon and (b) baryon-baryon scattering.

The validity of the Pomeranchuk theorem depends only on the assumed vanishing of the structure functions at $x = 0$, causing $\Delta\sigma$ to fall as $s \rightarrow \infty$. It is then trivial to modify $\sigma^{aa'}(Q^2)$ to act differently for quarks and antiquarks, without disturbing the Pomeranchuk theorem.

Fig. 6. Predicted total cross section contribution $\Delta\sigma$ due to a parton-parton interaction of the form $\sigma^{aa'}(Q^2) = \sigma_0 \theta(Q^2 - Q_0^2)$ (independent of a and a'). The contribution is shown in units of σ_0 for (a) meson-baryon and (b) baryon-baryon scattering. Both curves approach 1 for $s \rightarrow \infty$, so that in order for the Pomeranchuk theorem to remain valid, one must have $\sigma^{aa'}(Q^2) = \sigma^{a\bar{a}'}(Q^2)$ when allowing this quantity to depend on specific quarks.

Note: If the structure functions do not vanish at $x = 0$, the present model encounters difficulty with the Pomeranchuk theorem from very low $-Q^2$ contributions to $\sigma^{aa'}(Q^2)$, which are bound to behave differently for particles and antiparticles. On the other hand, the present parton ideas are probably not valid for such low values of Q^2 .

FIGURE 1(a)

FIGURE 1(b)

FIGURE 1(c)

FIGURE 2

FIGURE 3 (a)

FIGURE 3 (b)

FIGURE 3(c)

FIGURE 4

FIGURE 5

FIGURE 6