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STRONG INTERACTIONS AND THE 200 GeV ACCELERATOR

Geoffrey F. Chew

March 29, 1967

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I. INTRODUCTION

One of the goals of experiments to be made accessible by the 200 GeV accelerator is a unified description of all strong interaction phenomena--a description based on a small number of simple and esthetically attractive principles. Such a goal may not be reached, but the evidence available today justifies setting our sights at least this high. I say "at least" because all of us believe a unification of strong interactions with weak and (or) electromagnetic interactions to be a development that must eventually come. The only question is, "when?".

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The program today instructs me to concentrate on strong interaction physics as a separate subject and such an instruction makes sense, because specific arguments can be given that the contemplated increase of energy will be of qualitative value to the internal development of a strong interaction theory. This talk will review certain of these arguments. As a basis, let me begin with a brief survey of the existing state of knowledge.

II. ALREADY ESTABLISHED FEATURES OF STRONG INTERACTIONS

A. The outstanding achievement of the past two decades of strong interaction physics has been the experimental verification that all known hadrons, from excited states of transuranic nuclei all the way down to the pion, share an essentially equivalent status as "composite" particles. This verification has developed gradually, and one cannot assign to any single experiment a crucial role. For hadrons with baryon number greater than 1 a composite status has long been recognized, but early confusion over the status of hadrons with $B = 0$ (mesons) and $B = 1$ (baryons) is historically reflected in the oft-employed practice of calling these latter particles "elementary".

So long as physicists knew of only a few baryons and mesons, the notion of "elementary particles" could be maintained, but as the established number grew and grew and the spectra came more and more to resemble those for $B > 1$, the conclusion that we are dealing with a hadron democracy became inescapable. The beautiful and amazing discovery of SU_3 multiplets accelerated this conclusion. Two aspects of SU_3 deserve special mention in this regard: (1) One particular hadron, the pion, turned out early in the game to be distinguished by having a mass several times smaller than any other. As an inevitable result it plays a quantitatively more prominent role than its colleagues in a number of phenomena. However, many tentative theories

went further and assigned to the pion a qualitatively special role on the basis of its small mass. We might still be tempted by this idea of a mass distinction between hadrons if the pion had not been shown to fit nicely into an SU_3 octet, whose remaining members have more normal masses even though their properties otherwise are similar to those of the pion. (2) A few $B = 0$ or 1 hadrons, such as the nucleon, are distinguished by their stability with respect to strong interaction decay, and there consequently was temptation to assign a special role to these stable particles, relegating all unstable hadrons to a composite status. The discovery, however, of the baryon SU_3 decuplet put an end to the idea of stability distinction: One member of the decuplet turned out to be stable and the remaining nine unstable.

The notion that low spin might be a qualitatively distinguishing trait faded with the discovery of rotational sequences for baryons connecting very low with very high spins, sequences that look for all the world like the familiar rotational excitations of hadrons with large B . Such sequences are appearing now also for mesons. It seems almost certain at this point that all currently established hadrons lie on Regge trajectories. A corollary is that for $B = 0, 1$ as well as for $B > 1$ we are dealing with an infinite hadron spectrum, the low lying states being more

accessible but the total established number at any given time being limited only by the patience and ingenuity of experimenters.

Another corollary is the absence of any hadron parameters, like the fine structure constant of electrodynamics, which can be regarded as fundamental. We of course can define and measure particle masses and coupling constants, but these parameters are not independent of each other and none have a distinguished role. With appropriate choice of units, in fact (and apart from symmetry constraints) all hadron coupling constants seem to be of order unity.

High energy physicists have been so attuned to the search for elementary particles that some regard the verification of hadron democracy as a disaster for the profession--a whole generation of effort down the drain, the exalted status of high energy nuclear physics having been reduced to that of "ordinary" nuclear physics. I do not share this gloom, finding exciting the prospect of a revolutionary alternative to the centuries--old concept of elementary particles. In any event, we may draw from these considerations the most dramatic single question yet to be identified as a target for the 200 GeV accelerator: Is there after all, underlying the known and complex hadrons, a small group of undiscovered particles whose properties are so simple that they will deserve the title "elementary". You all are aware that SU_3 triplets, the so-called "quarks", are the currently fashionable

candidates for such a role. There is uncertainty as to the properties of quarks, if they in fact exist, but they must be substantially more massive than the low lying hadrons to have eluded observation. With luck, the extra energy from the new accelerator might put us over a quark threshold.

I for one would be disappointed if elementary quarks were found, for such a development would seem to return physics to the conceptual level already reached forty years ago. No basic questions would have been answered; the scale of discussion would simply have been reduced. In fact, it is recognized by theorists on a widespread basis that the naive view of quarks as small, simple, highly massive objects, which can combine with each other in tightly bound configurations, is inherently inconsistent. The forces to generate interquark binding would necessarily render individual quarks as large and as complicated as any other hadron. Thus, even if SU_3 triplets are discovered, they will probably have little connection with the elementary-quark hadron models that lend stimulus to the triplet search. Still, one must look for quarks and the 200 GeV accelerator will extend significantly our hunting capability.

B. A second important achievement of high energy hadron physics has been mentioned--the discovery of a multiplet structure among $B = 0, 1$ hadrons that was unforeseen on the basis of the low excitation studies of hadrons with $B > 1$. SU_3 symmetry

is by now familiar, but we must not forget that this is a broken symmetry and the meaning of the "breaking" remains obscure. Thus an obvious second question to be attacked by the 200 GeV accelerator is to what extent the "goodness" of SU_3 symmetry is a function of energy and momentum transfer. If SU_3 has a dynamical origin, like the shell structure of hadrons with large B , and the reason for its breaking is dynamical, one may expect regions where its violation becomes much greater than in the region where it was first discovered. If on the other hand the origin is closely related to some fundamental nuclear property, the violation may diminish in appropriate circumstances. Since the characteristic energy of strong interaction phenomena appears on the whole to be ~ 1 GeV, the contemplated increase of center of mass energies to ~ 20 GeV, with corresponding increases in momentum transfer, should be significant in this regard.

The SU_3 line of thought, furthermore, reminds us that there may be as yet undiscovered symmetries, with associated new quantum numbers, whose multiplet structure will require higher energies to be revealed. I am not aware of compelling theoretical arguments for further conserved quantities like strangeness, but, again, one certainly must look.

C. A third major accomplishment of hadron physics, shared between high and low energy experiments, has been the establishment of the analyticity of reaction amplitudes as functions of particle

momenta. Individual hadrons correspond to the poles of the scattering matrix, the remaining singularities being branch points whose location and character follow from unitarity once the poles are given. This analytic structure has been verified through a great variety of dispersion relations--the term physicists employ for the Cauchy formulas expressing analytic reaction amplitudes in terms of pole residues and cut discontinuities. Obviously it will be desirable to extend in energy the tests of dispersion relations, but I cannot at this time report any arguments for expecting a breakdown of analyticity to be revealed by going to 200 GeV. On the contrary, it seems logical to anticipate that analyticity will be accepted as a major tool, like conservation laws and unitarity, to be used in the interpretation of experimental results.

D. Closely related to the analyticity question but deserving of special mention has been the experimental verification and generalization of Yukawa's idea concerning the dynamical origin of the forces between hadrons. In a sense which is precisely understood in some respects and roughly understood in others, these forces arise from the exchange of hadrons. Since there is an infinite number of hadrons the forces are infinitely complicated, but fortunately the long range aspects are dominated by the lowest mass hadrons, the ones about which we have the most information. The argument is familiar that, by going to the higher momentum

transfers made possible by the 200 GeV accelerator, we shall be able to probe correspondingly shorter range aspects of hadron forces. The sense in which this probing is likely to be interpretable, however, is so far removed from Yukawa's original picture that discussion must be deferred to a later portion of my talk.

E. A final broad aspect of our existing understanding of strong interactions is the power law behavior with large energy at fixed momentum transfer. The maximum possible power is 1, according to both experiment and theory; experimentally this power seems reserved to those reactions (like elastic scattering) where the exchanged quantum numbers are those of the vacuum. With non-vacuum exchange the bounding power has turned out to be less than 1 and furthermore to decrease as the momentum transfer is increased. An important aspect of 200 GeV research will be to investigate whether these decreasing powers have a tendency to level off (say at -1) for large momentum transfer or to continue the downward trend now seen. This behavior should throw light on the existence of an elementary particle substructure for hadrons. An equally important objective is to establish whether or not a fixed power (equal to 1), independent of momentum transfer, is associated with vacuum-like exchange, placing this class of reactions on a qualitatively different footing from all others. In the simplest concrete terms, the latter question

amounts to asking whether elastic cross sections approach constants or whether they decrease slowly as the energy increases. A clear answer will have enormous impact on the development of theory, current confusion over the vacuum quantum numbers constituting a major roadblock.

I should also recall the recent raising of the startling question as to whether the vacuum power, even at zero momentum transfer, is exactly equal to 1. In other words, do total cross sections approach constants or do they asymptotically vanish. The power 0.93, for example, has been adduced from certain theoretical arguments, corresponding to total cross sections that would vanish as $E^{-0.07}$. Obviously this is a matter of prime importance, to be studied through precise measurements of total cross sections. (Changing the energy by a factor ten gives a 15% change in $E^{0.07}$.) If, incidentally, the vacuum power turns out to be less than 1 then this power would be expected to vary, like the non-vacuum powers, with momentum transfer, all theoretical arguments for a fixed power being linked to the special value 1.

III. HINTS FROM THE EXISTING DATA

Now let me pass from well-established ideas to a variety of intriguing hints that have recently arisen. Since these hints have evolved in a time interval $\lesssim 5$ years and remain in a state of flux, it is unlikely that many of the questions which they lead us to ask today will seem relevant at the time when the 200 GeV machine begins operating. Still, it may be instructive to speculate on how such a machine might respond to such questions if it were available today.

A. First there are the already mentioned quark models of hadrons, which have successfully correlated a substantial number of hadron facts and make many predictions. The most obviously relevant correlations for the 200 GeV machine are the ratios of high energy reaction amplitudes at small momentum transfer, such as the 3:2 prediction for the ratio σ_{NN}^{tot} to $\sigma_{\pi N}^{\text{tot}}$. If the new accelerator leads to beams of short-lived particles such as Λ 's and Σ 's, whose total cross sections could be measured at energies above 5 to 10 GeV, one could test previously unchecked quark-model predictions such $\sigma_{\Delta N} = \sigma_{\Sigma N} = 32$ mb. (It would be amazing in view of SU_3 , however, if $\sigma_{\Delta N}$ and $\sigma_{\Sigma N}$ were very different from $\sigma_{NN} = 36$ mb, and quark models are not usually claimed to be more accurate than 10%, so theoretical conclusions from such measurements may be indecisive.)

B. A second aspect of high energy reaction theory stands in greater obvious need of an energy step-up. This is the so-called Regge pole hypothesis, which attempts to correlate the previously mentioned power behavior of reaction amplitudes at fixed momentum transfer with sequences of particles in crossed reactions. A well-known example is the reaction $\pi^- p \rightarrow \pi^0 n$, where the leading energy power is supposed to correlate with the $I = 1$, $Y = 0$ meson sequence $1^-, 3^-, 5^- \dots$ that begins with the ρ . A host of general issues surrounding the Regge pole hypothesis is illustrated by questions now being asked about this particular example, questions which all would benefit greatly from a tenfold energy step. (1) Does the ρ trajectory fall indefinitely with increasing momentum transfer? An indefinitely falling trajectory, according to present theoretical ideas, would mean that the ρ is not composed of elementary particles (such as 2 quarks) but of composite particles which are composites of composites...and so ad infinitum. (2) Will the minimum in the $\pi^- p \rightarrow \pi^0 n$ cross section, which appears at or near the point where the ρ trajectory crosses $J = 0$, be repeated at $J = -2, -4$, etc., as simple theoretical reasoning suggests? (3) What is the energy dependence at this minimum--where the ρ pole spin flip contribution vanishes? Certain theoretical arguments predict also a vanishing of the ρ non spin-flip term. If so, other J-plane singularities must play

the controlling role at the minimum and the energy power here will be correspondingly different from zero. (4) What is the energy and angular dependence of the charge exchange polarization, which arises from an interference between the ρ pole and some other singularity or group of singularities? The nature of this dependence can tell us whether the additional singularity is another pole, a branch point or a combination related to direct channel poles.

Certain issues not raised by this first illustration are exemplified by the reaction $np \rightarrow pn$ and the companion $p\bar{p} \rightarrow n\bar{n}$. The extremely sharp forward peak observed here up to 10 GeV is supposed to be somehow associated with the π trajectory, but the π lies ≈ 0.5 units of J below the ρ . Therefore the relative strength of the ρ contribution to the cross section should increase by a factor 10 when the energy is increased by a factor ten and the forward peak should become broader--in conflict with naive intuitive expectations. Furthermore, in Regge terms, the π trajectory alone cannot produce the forward peak, interference with another trajectory (not the ρ) being required. One possibility is a 0^+ trajectory which crosses the π just in the forward direction: this is the mechanism called "conspiracy", which is related to a special symmetry developed at zero momentum transfer. Another possibility is interference with the first daughter of the A_1 , which lies exactly one unit of angular momentum below the A_1 (in the forward direction). These two possibilities

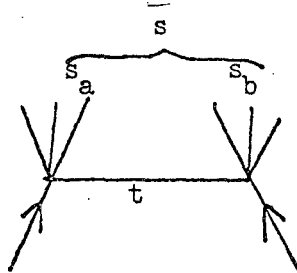
could be distinguished by the energy dependence of the reaction if this dependence were known over a wider interval than currently available.

There are many additional qualitative questions concerning the Regge pole hypothesis to be resolved by a large increase of energy, but the foregoing perhaps are sufficient to illustrate the current crop of puzzles.

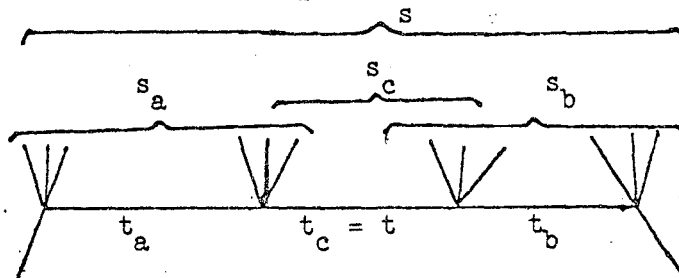
C. A quite different and highly intriguing subject of recent speculation has been the possibility of exponentially decreasing behavior for reaction amplitudes when momentum transfer is increased (or when energy and momentum transfer are increased together, as when the reaction angle is held fixed). The idea of a universal asymptotic exponential dependence on transverse momentum has not fared too well in recent experiments at Brookhaven and CERN but might well revive in the 200 GeV range. In any event, existing data suggests some kind of exponential law, and if the asymptotic law turns out to be simple it could have a profound effect on the development of theory. Thorough exploration of this question requires experiments in which both energy and momentum transfer are large compared to 1 GeV, while at the same time the first of these quantities can be made large compared to the second. Evidently energies in the hundred GeV range are needed.

D. Multiple Production

A collection of phenomena almost inaccessible to existing accelerators, which will be opened up by the 200 GeV machine, are the multi-peripheral reactions.* An ordinary (singly) peripheral reaction may be represented by the picture



where the momentum transfer $\sqrt{-t}$ is < 1 GeV while at the same time the energy \sqrt{s} is $\gg 1$ GeV. Such a kinematic situation requires the "cluster masses" $\sqrt{s_a}$ and $\sqrt{s_b}$ to satisfy the inequality $s_a s_b \lesssim st$ and it is a familiar fact that the preponderance of observed reactions fall into this category for $s \lesssim 40$ GeV², with $s_a, s_b \lesssim 6$ GeV². Now, clusters of mass $\sqrt{s_{a,b}} \lesssim 2-3$ GeV are of marginally sufficient energy to themselves manifest a predominantly peripheral structure, but had we started with 200 GeV lab energy, or $s \approx 400$ GeV², then the small momentum transfer requirement would permit $s_a, s_b \lesssim 20$ GeV², and multi-peripheral analysis becomes possible. That is, as shown



* I use this term in a phenomenological sense, not to describe any particular theoretical model.

in the figure, we may break each of the clusters a, b up into two smaller clusters such that all three momentum transfers t , t_a and t_b are small.

Theoretical study of the multi-peripheral mechanism, which obviously can be extended indefinitely as the energy increases, has yielded qualitatively encouraging correlations of the meager data from cosmic rays--particularly the so-called "fireball" phenomena. Quantitative investigation will require an accelerator, however. For example, there exists a close connection with the Regge pole hypothesis, whose natural extension predicts a behavior

$$\begin{matrix} \alpha_a(t_a) & \alpha_b(t_b) & \alpha_c(t_c) & \dots \\ s_a & s_b & s_c & \dots \end{matrix}$$

To check a distribution involving so many variables evidently will require an enormous number of events, far more than can be provided by cosmic rays.

IV. CONCLUSION

I began this talk by formulating one of the 200 GeV accelerator goals as a "unified description of all strong interaction phenomena--based on a small number of esthetically attractive principles". What relation exists between this broad objective and the specific topics touched in the foregoing? Let me illustrate some possible connection through a confrontation of ideas which, grossly oversimplified, has been described as, "quarks versus bootstrap". I am now using the term "quark" to stand for any entity, particle, field or otherwise, that represents an elementary (pointlike) constituent of hadronic matter. In contrast, the term "bootstrap" stands for a hadronic regime in which the concept of elementary constituent is totally absent, requirements of self consistency between unitarity and analyticity being the key to the puzzle.

On the basis of present knowledge, one can conceive of reaching the goal via either quarks or the bootstrap. The former concept is an extension of a line of thought familiar to physicists, and even putting aside the naive version of structureless elementary particles, it can be imagined that, as the energy increases, evidence for an ultimate point-like basis for nuclear matter will reveal itself. The presence in asymptotic expansions either of fixed powers or of powers that approach limits (like -1) might be so interpreted. So might the discovery of simple cross-

section ratios (like $3/2$) that become asymptotically exact.

The absence of simple and exact integer rules would, on the other hand, tend to support the bootstrap idea. Furthermore, the experimental elucidation of the properties of Regge trajectories and residues may provide the key to a systematic theoretical approach reconciling unitarity with analyticity. In other words, the bootstrap concept might be given mathematical respectability. The hint from existing data that trajectories arise indefinitely on the right and fall indefinitely on the left, with exponential residues, is already exerting on bootstrap theory a profound influence.

Quark or bootstrap, we need not doubt that the 200 GeV accelerator will contribute enormously to the final theory of strong interactions. With luck, the contribution may be decisive.

Thank you

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