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THEORETICAL PHYSICS AT NAL

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Theoretical Physics at NAL

The essays collected here are written by members of the Theoretical Physics Group at NAL on the present status of particle theory in general, and theoretical researches done and planned at Theoretical Physics Group in particular, and their aspirations. These essays are written in lieu of a general report to the Director on the activities of the Theoretical Physics Group. I am grateful to members of the Group for sharing in this labor.

In these essays we try to show the relevance of theoretical physics to the mission of the National Accelerator Laboratory as a national high energy research facility. But in a larger sense, what we would like to argue implicitly is that, to paraphrase the late Robert Oppenheimer, without further penetration into the realm of the very small, both theoretically and experimentally, the indomitable human reason may this time not triumph, and this is what is at stake.

B. W. Lee

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High Energy Hadron Physics

(H. D. I. Abarbanel)

The present significant questions in the high energy scattering of hadrons center around (1) the 10 percent rise in proton-proton total cross sections observed at the CERN-ISR over a range of equivalent laboratory momentum of 400 to 3000 GeV/c, (2) properties of inclusive distributions at large and small momentum transfers and correlations among produced particles, and (3) detailed properties of prong distributions at large s with special emphasis on the shape of $\sigma_n(s)$ as a function of n at fixed s. This is germane to the issue of possible two (or more) production mechanisms underlying hadronic amplitudes.

The group of theoretical physicists at NAL who have turned their attention to these issues include H. D. I. Abarbanel, J. Bartels, J. B. Bronzan, M. B. Einhorn, S. Jackson, J. -M. Wang, and A. R. White. Since a significant amount of activity has focused on the issue of rising cross sections and Pomeranchuk exchange (Pomeron) which governs the asymptotic behavior of $\sigma_T(s)$, I will describe this briefly here.

It is both possible and convenient to translate the behavior of $\sigma_T(s)$ in s into the language of complex angular momentum which is the conjugate variable to log s. Changes in the detailed structure of partial wave amplitudes in angular momentum reflect themselves in the detailed growth or fall of $\sigma_T(s)$ with powers of log s. Precisely this kind of behavior is at question in the interpretation of the CERN-ISR results. The experiments both have become so accurate (errors of order ±2 %) and have been extended over a large enough range in log s [$(\log s)_{AGS} \simeq 4$, $(\log s)_{NAL} \approx 6$, $(\log s)_{ISR} \approx 8$] that heretofore unobservable variations in log s are now key physical issues.

Any $\sigma_T(s)$ rising or falling with only powers of log s has its asymptotic behavior determined by structure in ℓ (complex angular momentum) at $\ell = 1$. A pole at $\ell = 1$ yields $\sigma_T(s) =$ const., a dipole, $\sigma_T(s) \simeq$ logs, etc. When there is singularity structure at $\ell = 1$, unitarity requires that this structure repeat itself, and the singularities pile up into what a priori would seem to be a complicated situation. A technique for handling this interaction of poles and branch cuts was developed several years ago by V. N. Gribov. He showed on the basis of a study of Feynman graphs in model field theories that, viewing the interacting objects (called Reggeons by the practitioners) as quasi-particles in a quantum field theory, one could establish a calculus for the systematic study of their interaction. Using powerful techniques developed by modern field theorists, our group has made significant progress in cataloguing the kind of structure near $\ell = 1$ which is allowed by the full many Reggeon unitarity. We find, for example, that when there is a basic Yukawa-like coupling of the Reggeons, the total cross section must rise slowly as $(\log s)^{\mu}$ with a power μ on the order of 1/6. The power can be calculated by a perturbation series in a small parameter of the theory.

Other basic couplings governing the interactions of the quasi-particles are being investigated. The field theoretic techniques can be generalized to the study of corrections to the gross behavior in charge exchange scattering at high energies and, if pushed, show some promise to enable one to understand some of the structure in elastic differential cross sections as measured here at NAL. Many of these things are results to expect in the future, and the prospects are tantalizing and the physics exciting.

Rising Total Cross Sections

(M. B. Einhorn)

There has been a number of phenomenological proposals which claim to explain the cause of the rise in the proton-proton total cross section σ_{TOT} seen at the ISR. Three competing hypotheses, each of which claim to account for the entire rise, attribute the increase to (1) the diffractive excitation of one of the protons, (2) the rapid increase in the production of antiprotons, also seen at the ISR, (3) the growth in the proton radius described by the eikonal model of Cheng and Wu, as applied phenomenologically by J. K. Walker.

(1) The first hypothesis correlates the diffractive peak seen at the ISR and at NAL (and used as evidence for the non-vanishing of the triple pomeron coupling) with the increasing total cross section. Under a variety of specific theoretical assumptions, one can show that this diffractive peak will contribute to an increase in σ_{TOT} (effectively like ℓn s) over the ISR energy range. However, numerical estimates by Einhorn and others indicate that this mechanism can account only for about a 2 mb increase in σ_{TOT}. If one assumes a turnover at small t (for a range in the missing mass), such as seen in NAL Exp. No. 14A, (Columbia-Stony Brook), then the increase will be even less. This proposal has also been criticized on theoretical grounds because the same diffractive mechanism responsible for the peak causes absorption in non-diffractive production processes. Blankenbecler has shown that

this absorption causes a decrease in σ_{TOT} which is precisely twice as great as the increase naively expected.

(2) A second proposal takes note of the fact that the production of antiprotons rises very rapidly over the ISR energy range. Several multiperipheral models have been constructed which suggest that this could possibly explain the rise in σ_{TOT}. However, it has been pointed out (by Einhorn and Nussinov) that these models neglect some important effects of unitarity and that, when unitarity is taken into account, it is no longer clear that this explanation is correct.

(3) Interest in the geometrical model of Cheng and Wu has been revived by the increase seen in σ_{TOT}. In this approach, a hadron ultimately becomes a black disc with a radius increasing with the log of the energy, asymptotically giving a total cross section growing like $\log^2 E$. In a series of fits, J. K. Walker has applied these ideas to known data and made a number of interesting predictions for the ratio of the real to imaginary part as well as for other total cross sections which will be measured here at NAL in the Meson Lab.

It remains a mystery whether the rise in σ_{TOT} is indicative of something important and, possibly, fundamental about hadronic interaction or whether it is just an uninteresting accumulation of a variety of contributions to inelastic multiparticle production.

Quark-Parton Models

(M. B. Einhorn)

In this section, I will describe further developments of the idea that hadrons can be usefully described as composed of elementary constituents (partons) which, in certain circumstances, can be regarded as weakly interacting. A particularly appealing hypothesis has been that the charged partons are, in fact, quarks. In the past year or two, theoretical advances in the application of light cone analysis to decays such as $\pi^o \rightarrow \gamma\gamma$ suggested that, while the charged partons may be quarks, very probably these quarks carry another quantum number (currently called "color") and that there are probably at least three different colors. A hadron, instead of being composed of three different quarks, is composed of 3 different color triplets or 9 quarks altogether. Another advantage of having an additional quantum number is that, by making a nucleon antisymmetric in the color, the quark model recovers the usual relation between spin and statistics. A particularly sensitive test of the number of elementary constituents coupling to the electromagnetic current is the ratio $R = \sigma_T(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. In any parton model, this ratio should be asymptotically constant and equal to the sum of the squares of the charges of the constituents. Without color, this ratio should be $\frac{2}{3}$ $[Q_u^2 + Q_d^2 + Q_s^2 = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3}]$. Introducing 3 colors, the ratio becomes three times as large or $R = 2$.

If the elementary constituents are not quarks, but something else, the ratio will be different. There was some indication from CEA that this ratio might be large and growing with energy, but the errors were large. At the Irvine Conference on Dec. 7-8, 1973, the first preliminary results from SPEAR were reported indicating that this ratio increases from the value ~ 2.5 at an energy of 3 GeV to the value ~ 5.5 at 5 GeV. As the preceding discussion indicates, the large value itself threatens the conventional quark-parton model. However, different parton models give different values for this ratio. On the other hand, the rise, if indicative of the asymptotic behavior, threatens all parton models.

It is important, therefore, to interpret the new data from SPEAR carefully and to have additional tests of parton models. As is well known, many of these will come from NAL muon and neutrino experiments. More theoretical work on parton phenomenology is well justified, and here at NAL, Einhorn and Savit have been exploring consistency relations between different experiments required by such models. For example, given the data on νW_2 for protons and neutrons, a rigorous upper bound exists for the cross section for $pp \rightarrow \mu^+\mu^- X$ in the context of various parton models. Also, given the preliminary data from Gargamelle on the cross sections for $\nu N \rightarrow \mu^- X$ and $\nu N \rightarrow \mu^+ X$, further restrictions can be derived. One can also show that these results imply that on the order of 40 percent of the momentum of the nucleon must be carried by neutral partons.

Hadronic Physics at Large Transverse Momenta

(R. Savit)

A nearly universal feature of high energy hadronic interactions is that the final state particles typically have quite small transverse momenta. This suggests that hadrons are rather fragile objects--that if you try to kick one very hard, it breaks up so that the probability of finding a given hadron with a large transverse momentum is very small. If all strong interactions were "soft" in this sense, then one might expect the standard parameterization of hadronic cross sections $\sim e^{-AP_\perp}$ which is a good fit near $P_\perp \approx 0$ to describe the data even out to quite large $P_\perp$. However, recent experiments here at NAL and elsewhere indicate that this is not the case. (The present experimental situation was reviewed by L. Lederman at the recent NAL mini-conference on Large Transverse momentum phenomena, which was organized by the theory group.) The yield of hadrons at large $P_\perp$ is much larger than predicted by a naive extrapolation of the fits to the small $|t|$ cross sections. The implication is clear: it is not sufficient to think of strong interactions as only soft--there is a hard component as well, the effects of which are directly revealed in experiments at large $P_\perp$

Several models have been proposed to explain (and in some cases predict) the behavior of hadronic amplitudes at large $P_\perp$. While many of them show some common features and are even successful at describing certain aspects of the data, none is completely satisfactory from a theoretical viewpoint. I will briefly describe the most promising of these models, and then discuss some of intriguing possibilities for trying to understand them at a deeper level.

All the models I will discuss picture the physical hadrons as being composed of quarks. The simplest model for large angle hadronic scattering assumes that a quark from each hadron scatters through a large angle, and then by some (mysterious) mechanism fragments into real hadrons. The simplest versions of this theory (for example, quark scattering via single gluon exchange) do not describe the present data, although the proponents argue (with some justification) that the energies and momentum transfers are simply not high enough to see this process emerge. On the other hand, a model which gives an adequate description of large angle scattering data was first proposed by Blankenbecler, Brodsky and Gunion. They assume that the strong interactions take place via the interchange of hadronic constituents (assumed to be quarks). A large number of predictions follow from this model, none of which are in disagreement with the present data. A third picture of large angle scattering was suggested by Brodsky and Farrar. They again assumed that hadrons were composed of quarks (3 for baryons, 2 for mesons) and examined Born graphs in renormalizable field theories. Their predictions, while not as extensive as those of the interchange model, agree for the most part.

In view of these developments, the important theoretical problems in this field are the following: 1) Does large angle hadronic scattering really expose the simple, fundamental processes of the strong interactions? 2) If so, what are they? In particular, is it true that at large energies and momentum transfers the behavior of the hadronic cross section will again change? 3) What is the relationship between the two classes of models that give similar predictions? Are they just different ways of saying the same thing? What is the theoretical justification for considering only Born graphs in renormalizable field theories? This question may be answered by considering asymptotically free gauge theories, and the answer to this question may also answer the following question. 4) Why don't the quarks get out? 5) What is the relationship between the hard interaction which gives rise to large angle scattering and the soft ones responsible for small angle scattering? An answer to this question has been proposed by Blankenbecler, Brodsky, Gunion, and Savit, and further work is continuing. Finally, it is important for the theorist to help devise ways of phenomenologically discriminating between various models, and work along these lines is also in progress.

It is clear that very little is understood about this area of strong interactions. Much theoretical and phenomological work remains to be done, and it is a testimony to the excitement of this field that the number of question marks in this report is of the same order of magnitude as the number of periods.

Weak Interactions

(B. W. Lee)

Electromagnetism, as it has been understood since the times of Faraday and Maxwell, is a classic example of scientific triumph. Not only did it unify two diverse phenomena--electricity and magnetism--in a beautiful set of mathematical equations, but also it had profound predictions to make--for example,the propagation of electromagnetic waves, as later confirmed by Hertz. The unification of disparate phenomena in a single conceptual framework is in the best tradition of theoretical physics; to understand our physical universe in one conceptual system is the ultimate goal of physics, and unification allows us to make a number of new predictions, which are logical consequences of the whole, and not of its components. It is no wonder that Einstein dedicated his later life to the unification of gravity and electromagnetism.

Recent advances in weak interaction theory came about from various attempts to unify electromagnetic and weak interactions of elementary particles. There have been proposed a number of models along these lines. We dc not know yet which model, if any at all, describes the real world, but already these attempts have solved an outstanding theoretical problem. The conventional theory due to Fermi, Feynman and Gell-Mann is quite satisfactory in describing low energy gross features of weak interactions, but yields meaningless results for certain "high order" effects and for high energy behavior. Through the recent efforts we now know how to construct a weak interaction theory which agrees with known low energy phenomenology and which gives unambiguous and finite answers for all higher order effects. The Theory Group at NAL has contributed very heavily to these efforts, that is, in showing the "renormalizability" of this class of theories based on "gauge principles."

A very general consideration says that a finite theory of weak interactions must predict neutral currents and/or a new kind of lepton--a massive form of electrons and muons. The Theory Group has been very active in assaying the existence of these effects in existing data, and in suggesting new experiments to look for the effects of neutral currents. A somewhat surprising fact is that there seems to be no strangeness changing neutral current in nature (as deduced from the absence or suppression of processes like $K_L \rightarrow \mu\bar{\mu}$, and $K \rightarrow \pi + \nu + \bar{\nu}$), and this prompts a number of speculations as to the existence of a fourth quark. At NAL, various consequences of such a new constituent of hadrons have been and are being studied.

There have been speculations that the strong interaction of hadrons are also governed by a gauge principle, and that, ultimately, all three interactions of hadrons--strong, weak and electromagnetic--have to be understood in a unified manner. These speculations are prompted by the possibility that, in such a theory, one may find very natural explanations to the puzzles as to why free quarks are not seen in nature, but exist only inside hadrons, and why quarks behave as if they were free within a hadron. Such a development may also shed some light to the question of why there are three classes of interactions in the first place, and may bring about a number of new predictions as well as illuminate deeper questions. The possibility is, to say the least, tantalizing.