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THEORETICAL PARTICLE PHYSICS

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The research work completed since December 1, 1970, when the theoretical part Task B of the AEC Contract AT(11-1)-2009 was first initiated, falls into two categories. The first, which has been by far the main thrust of our work, concerns the development and exploration of a model to describe particle reactions at all scattering angles. The second concerns the application of duality diagrams to particle scattering, as well as the proposal by one of us of a quark model for leptons.

I. PARTICLE SCATTERING AT ALL ANGLES

The original motivation for this work was provided by the experimental measurement¹ of pion nucleon elastic cross-sections at all angles (primarily by the Indiana Spark Chamber group, Task A) in the momentum range 2 - 5 GeV/c. More recently however, excellent data at 5 GeV/c and again at all angles have been forthcoming from Argonne² (π^+p , CEX) and CERN³ (π^+p , K^+p , pp , $\bar{p}p$) for a variety of processes, thus making the need for an all-angle model even more compelling.

The basic ideas of our model are by no means new, but are familiar to all atomic, nuclear and high energy physicists alike. The scattering is envisaged as taking place within a region of radius about 1F, the low partial waves being substantially absorbed and the peripheral waves possibly being enhanced by strong surface effects. Could it be that this well-known s-channel picture is applicable even in the scattering of elementary particles? We suggested in our Physical Review Letter⁴ that this was indeed the case, and showed that all the three well-known dips in π^+p CEX (at $t = 0$, -0.6 (GeV/c)² in the forward direction and at $u = -.2$ (GeV/c)² near the backward direction) could be accounted for simultaneously by scattering from the same peripheral

band of angular momentum states.

During the past few months, we have been able to test our model in two specific cases.

Analysis of π^+p elastic scattering from 2.74 to 4.0 GeV/c at all angles (Ref. 5)

π^+p elastic scattering was chosen as our first test case since the data in this momentum range are reasonably complete, with $d\sigma/dt$ at all angles, some forward and backward polarization, total cross-section and the ratio of the real to imaginary parts of the forward amplitude, all known. The low partial waves were parametrised by Gaussians in ℓ (suggested from, say, the Fourier-Bessel transform of a typical elastic peak e^{at} , or from the partial wave decomposition of $s^{\alpha(t)}$). The peripheral band of angular momentum states was parametrised as a Breit-Wigner in ℓ . This latter form is of particular importance: it is a Regge pole in the s-channel angular momentum plane. It is precisely this form which is appropriate to the scattering of grazing rays in classical scattering theory (originally derived by Sommerfeld⁶ who was considering the scattering of electromagnetic waves by a conducting (absorbing) sphere (the Earth), and later borrowed by Regge⁷ in his famous study of the Schrödinger equation).

We showed that it was indeed possible to fit all of the data on the basis of the simple physical picture described above. The consistency of the model was especially demonstrated by the fact that we found the Breit-Wigner to be centered around $0.8F$, which was precisely the place where the absorption was found to fall off rapidly. Another interesting result is that this same situation occurred for all four energies examined, so that the size of the interaction region remained constant over this momentum interval.

5 GeV/c pion-nucleon scattering at all angles (Ref. 8)

More recently, all-angle data^{2,3} for π^+p elastic and π^-p CEX at 5 GeV/c have become available. Studying these three coupled reactions provides a further stringent test of the model. We chose a slightly different parametrisation, suggested partly by our previous π^+p analysis. For example, diffraction was parametrised as a fermi distribution in the impact parameter b (rather than a Gaussian in t), a form well-known to be applicable in nuclear scattering. We still characterized the peripheral scattering by the classical s -channel Regge pole (in b), but allowed this time for possible exchange forces (also important in some nuclear scattering processes). Again a reasonable overall fit was obtained.

In this paper, we also briefly compared our explanations of various experimental structures (dips, cross-over, polarizations) to those of the more familiar Regge pole model which is based on exchanges (poles, cuts) in the crossed channels (there is of course no correlation between forward and backward scattering in the Regge pole model). Some of the explanations turn out to be essentially the same; others (such as for diffraction) are different. Likewise we made some comparisons with the recent dual-absorptive model of Harari.⁹ Harari also emphasizes the peripheral aspect of the scattering. (However, in his model, he discusses only forward scattering; moreover, he has still to make his model quantitative by suggesting a possible parametrisation for the amplitudes and fitting the actual data.)

This brings us to another important question -- what is the connection (if any) between our s-channel approach and the usual t, u-channel Regge models? We believe we have been able to at least partially answer this question.

On the Equivalence of Regge and Optical Models (Ref. 10)

In this paper, we show that these two apparently quite different models have in fact a great deal in common. This is done by partial wave analysing typical Regge terms (from poles plus cuts), and examining the partial wave amplitudes as functions of b , the impact parameter. Our major conclusions are as follows.

(1) The rotating Regge term is essentially equivalent to our s-channel Regge pole (Breit-Wigner), positioned at $b \approx 0.8F$; that is, it corresponds to the peripheral scattering.

(2) That b comes out to be about $0.8F$ is determined by the slope $\alpha' = 1$ of the Regge pole trajectory. Hence it is possible to understand the universality ($\alpha' = 1$) of the slopes of leading Regge poles, for both mesons and baryons: the Regge parametrisation for leading poles just reflects that the scattering is taking place from the $0.8F$ edge of the interaction region. Moreover, the radius of this interaction region remains constant at $0.8F$ for all (intermediate) energies.

(3) We are able to interpret Schmid loops -- they are due to the enhancement of the peripheral scattering.

Proton-proton elastic scattering at all angles

Recently, we have started analysing proton-proton elastic scattering at all angles, assisted by a graduate student Mr. T. Y. Cheng. In contrast to pion-nucleon scattering, the pp differential cross-section is comparatively smooth (though a pronounced shoulder at $t = -1.0 \text{ (GeV/c)}^2$ develops at the highest momenta, about 20 GeV/c). At present we have preliminary fits for momenta 3 - 10 GeV/c.

So stands our model and our interpretation of scattering at the present stage. We feel that our model has been profitable in analyzing all-angle data. We do not claim that our parametrisation is in any way unique, but at least it seems to have the right ingredients. Clearly we wish to continue our research in this area and to examine other reactions.

II. APPLICATION OF DUALITY DIAGRAMS, AND A QUARK MODEL FOR LEPTONS

This is the second area in which research has been completed. We discuss three papers in turn.

Duality diagrams with exotic t-channel exchanges in meson-baryon scattering (Ref. 11)

The Regge pole model together with the two-component concept of duality has been shown to be quite successful in correlating many features of hadron reactions at high energy. If one supplements the scheme with the

quark-model-motivated assumption of no exotic states in the s-channel, the impressive predictions of the exchange degeneracy of ρ - A_2 and K^*-K^{**} Regge trajectories, as well as the constancy of the K^+p and K^+n total cross sections, follow.

However, there are also certain areas where this simple model does not agree with experimental data. Notably: (i) the line reversed reactions $K^-n \rightarrow \Lambda\pi^-$ and $\pi^-p \rightarrow \Lambda K^0$; $\pi^+p \rightarrow K^+\Sigma^+$ and $K^-p \rightarrow \pi^-\Sigma^+$ have unequal differential cross sections and nonzero polarizations, and (ii) $\pi^-p \rightarrow \pi^0n$ and $\pi^-p \rightarrow \eta n$ have nonzero polarizations. One can argue that all these failures are due to the fact that only Regge poles have been included; presumably cuts or at least complex conjugate poles should also be introduced. However, unless we have additional rules governing the contribution of Regge cuts, much of the simplicity and predictive power of the Regge pole model is lost. Complex conjugate poles can explain nonzero polarization in πN CEX scattering and the nonequality of the differential cross sections in the hypercharge reactions, but then there is no reason why $K^+n \rightarrow K^0p$ and $K^-p \rightarrow \bar{K}^0n$ differential cross sections should be equal.

We have pointed out in this paper how it may be possible to include, within the framework of duality diagrams, additional contributions that will remedy all the major failures of the simple pole model while at the same time retaining the successful predictions and simplicity of the model. We show that this can be achieved if the usual assumption of no exotic states is relaxed, exotic t-channel exchanges, via for example double exchange of non-exotic mesons or Regge cuts, being allowed. One can determine unambiguously whether Regge-Regge cuts will or will not contribute to a given reaction. (It is interesting to note that some of the selection rules for Regge-Regge

cuts derived recently by Finkelstein¹³ from quite different considerations of double spectral functions, are the same as our rules derived from quark diagrams.)

Quark diagrams for cuts and poles (Ref. 14)

Here, we develop more systematically the scheme of quark (duality) diagrams discussed above. We point out that this diagram scheme, originally proposed for duality between Regge poles and resonances, is just as powerful when cuts are included. After discussing rules for constructing allowable quark diagrams, we conjecture that each one of the invariant amplitudes of a given reaction is a linear combination of these allowable diagrams. We argue that this conjecture is reasonable by examining many qualitative features of the experimental data. We then discuss the status of cuts in this scheme and find: (a) the Pomeranchuk singularity is a cut (it does not correspond to poles in any channel), (b) Regge-Regge cuts seem to be at least as important as the Regge Pomeranchuk cuts, (c) the Regge-Regge cut contribution in the forward direction is closely connected through analytic continuation to the Regge pole contribution in the backward direction. The asymptotic behavior of the diagrams in meson-meson and meson-baryon scattering is identified through their connection to the Veneziano model in the zero width approximation; in particular, we get an effective pole contribution which simulates the Regge-Regge cut. We argue that the Veneziano model in its present form is not applicable to baryon-baryon and baryon-antibaryon scattering, and outline the generalization of the diagram scheme to these latter cases.

A quark model for leptons (Ref. 15)

In recent years, quark, or parton, models seem to have had a considerable amount of success in hadronic physics. It is therefore not inconceivable that a similar model, based on quarks, exists for leptons. We have tried to explore, to some extent, this latter possibility.

We begin by assigning to the leptonic quarks, electric charges and spin as suggested by the hadronic quarks. The origin of the strong binding force responsible for the formation of leptons out of quarks, is taken to be the magnetic charges, suggested by Schwinger¹⁶ in his dyon model. The leptons are then identified by means of their leptonic quark compositions; intermediate bosons can also be identified in a natural way. It turns out that the observed mass differences are consistent with this model if we assume that the observed leptons have zero magnetic charge and belong to an octet of spin $\frac{1}{2}$ -- the mass breaking term transforms as the electric charge, in analogy with the usual SU(3) model for hadrons where the mass breaking term transforms as the hypercharge.

We next turn to the selection rules for weak interactions. Conservation of lepton numbers can be satisfied if we assign lepton numbers not only to leptonic quarks but also to the hadronic quarks. Other selection rules of weak interactions as well as CP violation can also be realized by assuming they are mediated through the intermediate bosons identified in this scheme. The absence of a neutral lepton current can be understood on the quark level as a consequence of magnetic charge conservation. Finally, the close parallel between the leptonic quarks and the hadronic quarks

leads us to speculate on a modified quark model which may serve to unify the leptons and the hadrons.

The two principal investigators are spending 100% of their time during two of the summer months and 40% of their time during the academic year, on the research project. Besides two seminars at Indiana University itself, the principal investigators have given during the year invited seminars at the University of Illinois, the University of Wisconsin, the University of Toronto, the University of Guelph (Canada), the Argonne ZGS Users' Annual meeting and at the June Argonne Workshop on Intermediate Energy Physics. In June, 1971, we took on a graduate student, Mr. T. Y. Cheng, who is working with us one-half time and assisting us at present in our analysis of proton-proton scattering.

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