relation over a substantially complete region of space as the external potential is turned on. For example, if one expands $\ln[ne^{\beta U}]$ in terms of $n$, large density fluctuations outside the range of $U$ will not be well represented. Indeed, this particular choice gives rise to

$$\beta V(x,y)+\ln[n_2(x,y)/n(x)n(y)]+1-n_2(x,y)/n(x)n(y) = -c(x,y), \quad (6)$$

which is the hypernetted chain approximation.[5] On the other hand, the same development applied to the relation between $n\nabla\beta U$ and $\ln[ne^{\beta U}]$ yields the B.B.G.K.Y. equation[4] in the form

$$\nabla_x \ln[n_2(x,y)e^{\beta V(x,y)}/n(x)]$$
$$+[\nabla_x \ln n(y)]\ln[n_2(x,y)e^{\beta V(x,y)}/n(x)]$$
$$+\int[n_2(x,z)/n(x)]\nabla_x\beta V(x,z)[n_2(y,z)/n(y)n(z)-1]dz=0. \quad (7)$$

While $n\nabla\beta U$ does vanish outside the range of force, the required linear relation within simply does not obtain; the precise effect is not easy to assess.

The superiority of the P.Y. equation for short-range forces and moderate densities is no longer obvious in other domains, with characterizations as diverse as: long-range forces, phase transitions, quantum fluids, etc. A detailed elaboration of the present viewpoint for the more general situation is now being prepared for publication.

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## IS THE PHOTON AN ELEMENTARY PARTICLE?*

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The idea that all strongly interacting particles are nonelementary in the technical sense of not being associated with quantized wave fields is a very attractive one. The possibility of associating such particles with trajectories of so-called Regge poles of the $S$ matrix regarded as an analytic function of a complex angular momentum has been widely discussed.[1-4] Unfortunately, it has not yet been possible to establish theoretically any of the "desired" properties of Regge trajectories in a relativistic theory.

It has been conjectured by Chew and Frautschi[2] that all of strong interaction physics (including predictions of particle masses, baryon conservation, strangeness, isotopic spin, etc.) will "flow" from the principles of maximal analyticity of the $S$ matrix, unitarity, and the concept of maximum strength of interactions compatible with unitarity. An attempt to axiomatize an $S$-matrix theory which makes no reference to fields has been made by Stapp.[5] From the standpoint of theoretical physics, the flow has thus far been more of a trickle than a deluge. Whether or not we know, yet, the proper basis for the Regge pole hypothesis, the concept seems to be a very useful one for high-energy physics phenomenology[6] and the question of "elementarity" can be tested experimentally.[4]

It is somewhat disturbing that any theory founded on such general principles as unitarity and analyticity should single out only strong interactions. The outstanding omission from the scene is the photon. Interestingly enough, this is the only object for which the field concept seems to have a very firm foundation in the theory of measurement. We would like to argue that since photons interact with all charged particles (including the so-called strongly interacting ones) if they are nonelementary, then the photon must be nonelementary as well.

If the present ideas about Regge trajectories in the strong interaction regime are correct, there can be no real distinction between weak and strong interactions, since the latter can be made arbitrarily weak in a scattering process by going to sufficiently high energies at a fixed momentum transfer. To see this, consider proton-proton scattering and make the assumption that at high energies the process is dominated by the vacuum Regge trajectory.[4] The matrix element is given by[7]

$$M_R = -\left[\frac{1+e^{-i\pi\alpha(t)}}{\sin\pi\alpha(t)}\right]\alpha(t)\,\frac{G^2(t)}{\mu^2}\,\gamma^{(1)}\ \gamma^{(2)} Z^{\alpha(t)-1}. \tag{1}$$

The spinors associated with the $\gamma$ matrices have been omitted; $t$ is the usual invariant squared momentum transfer, $G(t)$ is a form factor $[G(0)=1]$, and $Z=2[2mE+t/2]/(t-4m^2)$ with $E$ the laboratory energy. Also, $\alpha(t)$ is the vacuum Regge pole and $\alpha(0)=1$; the factors have been chosen to yield a total cross section of 40 mb.

On the other hand, if the photon were elementary, we would have from the one-photon exchange graph, with $F(t)$ the usual form factor,

$$M_P = -(e^2/t)F^2(t)\gamma^{(1)}\ \gamma^{(2)}. \tag{2}$$

In this expression, $e^2/4\pi = 1/137$. Since $Z\approx E/m$, at $t\approx -50\,\mu^2$ where $\alpha\approx 0$,[4] the "strong" interaction is overtaken by the "weak" at an energy $E$ given by

$$E = 2.5m(4\pi/e^2) \sim 340 \text{ BeV}. \tag{3}$$

We make the reasonable assumption $G(t)\approx F(t)$. Even at 30 BeV, the electromagnetic corrections are quite significant, of the order of 20% in the cross section.

We wish to advocate that the photon be treated just as the strong interactions. That is, we shall associate with the photon a Regge trajectory with odd signature which has the property $\alpha_1(0)=1$, corresponding to a spin-one zero-mass, physical photon.

We are not prepared to develop a complete theory of photon interactions including general features like gauge invariance, etc. What we shall do is to discuss some of the experimental consequences of abandoning the concept of photons with fixed angular momentum. Our inability to compute the slope of the photon trajectory makes it difficult to make quantitative predictions. We would, of course, expect it to be rather less than the slope of the vacuum trajectory ($\sim 1/50\mu^2$).[4]

The hypothesis that a virtual photon does not have spin one constitutes a way of describing a breakdown of electrodynamics which is quite different from the usual descriptions in terms of modified propagators. We have examined in detail the consequences of the present assumption for electron scattering from pions, nucleons, and $\alpha$ particles[8]; the general structure of the results will be true for any target.

The most obvious difference between the conventional discussion and the Regge analysis is the fact that all invariant amplitudes contribute to the matrix element. For example, in electron-pion scattering there are two independent functions of energy and momentum transfer instead of the usual single form factor depending only on $t$. Similarly, in electron-proton scattering there are six functions in place of two form factors. We are well aware of the fact that graphs involving two-photon exchange in the ordinary theory give rise to such a complication and we will return to this important point later.

For simplicity of presentation, we shall describe here only the modification of those amplitudes which reduce for spin-one photons, single-photon exchange processes, to the conventional form factors. Our analysis leads to "form factors" with the structure (for large $Z$)

$$F = (e^2/t)[G_1(t) + tG_2(t)Z^{\alpha_2-\alpha_1}]Z^{\alpha_1-1}, \tag{4}$$

where $Z$ is related to the laboratory energy, $E$, momentum transfer, $t$, and electron ($m_e$) and target ($m$) masses by

$$Z = \frac{2[2mE+t/2]}{[(4m^2-t)(4m_e^{\,2}-t)]^{1/2}}; \tag{5}$$

$\alpha_1(t)$ describes the photon trajectory and $\alpha_2(t)$ is the trajectory of the $T=0$ or $T=1$ pion resonances corresponding to odd signature. In writing Eq. (4) we have assumed that only one family of the latter is important. The term $G_2$ measures the direct coupling of the electron to the pion resonances. In ordinary electrodynamics, $G_2=0$ and $\alpha_1(t)=1$ for all $t$. We expect the $G_2$ term to be small under most circumstances but it would be interesting to see if it can be detected experimentally. The most prominent feature in Eq. (4) is the appearance of the over-all factor of $Z^{\alpha_1-1}$ which gives rise to a new energy dependence not found in lowest order electrodynamics. We wish to emphasize that there are three general modifications of the usual theory: terms of the above $G_2$ variety, additional "form factors," and the energy dependence of cross sections coming from the factor $Z^{\alpha_1-1}$ (which actually appears in all of the invariant amplitudes). All of these effects correspond to a breakdown of the familiar Rosenbluth formula.

From an experimental point of view, the easiest thing to detect should be the additional energy dependence arising from $Z^{\alpha_1-1}$. For spin-zero targets [neglecting $G_2$ in Eq. (4)] the ratio of cross sections for scattering at a fixed value of $t$ and two different energies $E_1$, $E_2$ is

$$\frac{\sigma(E_1,t)}{\sigma(E_2,t)} \approx \left\{1+2[\alpha_1(t)-1]\ln\frac{E_1}{E_2}\right\}. \qquad (6)$$

It is important to note that Eq. (6), as well as Eq. (4), is valid only for large $Z$, and Eq. (5) in turn implies that $E$ must be large and $(-t)$ must be moderate. For example, for $E=1$ BeV and a nucleon target, $t=-5\mu^2=2.5$ (fermi)$^{-2}$ and $Z\approx 6$, which is large enough. (This corresponds to a lab scattering angle of 20°.) To estimate the experimental accuracy required, let us assume that the slope of the photon $\alpha$ is as large as that found in strong interactions, namely $\alpha_1(t)-1 \approx t/50\mu^2$. Then for $t=-5\mu^2$, $E_1/E_2=1.5$, we find the ratio in Eq. (6) is 0.92. Ideally one wants to do the experiment at the largest values of $(-t)$ consistent with the available energies and the requirement that $Z$ be large compared to unity.[9] The forthcoming colliding beam electron scattering experiments will be extremely interesting to analyze from the point of view described here.[8]

We return now to the question of distinguishing the Regge behavior from the multiple-photon exchange graphs in the usual theory. A quantitative estimate of the latter effect can be obtained by comparing electron and positron scattering from the same target. This has been done by Pine and Yount[10] at about 400 MeV with a proton target and they find less than $\frac{1}{2}\%$ difference, which agrees with theoretical estimates. It would be quite surprising if the energy dependence of "form factors" in the conventional theory took the same form as that predicted by the Regge analysis.

There are a number of intriguing questions related to the present ideas to which we can at this time only draw attention. One would expect that electrons should be nonelementary and this would be interesting to test. Are there other members of the photon family with odd signature? Is there a spin-three resonance with the quantum numbers of a photon? Is there an even signature family leading to bound states or resonances with spin zero or two? Are there other vector resonances which are isotopic spin mixtures associated with the photon but which lie on lower trajectories? Is the vacuum trajectory a mixture of $T=0$ and 1 so that it forms the strongly interacting, even signature counterpart of the photon? Where does isotopic spin and its conservation enter the picture?

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