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ABSTRACT

The concepts of "elementary" and "composite" particles are reviewed, the status of the nucleon receiving special attention. It is concluded that the nucleon is probably not more fundamental than other nuclei but that sound practical reasons nonetheless exist for giving this particle concentrated experimental and theoretical study. The notion of nucleon "structure" is examined, the dubious status of the subatomic space-time continuum being emphasized, and it is argued that the most promising medium in which to seek an understanding of the origin and properties of a strongly interacting particle such as the nucleon is the momentum-energy continuum. Attempts to formulate fundamental laws in this framework are surveyed.

Our Conference is concerned with the structure of the nucleon. Why are we so interested in this nuclear particle? Is it reasonable to expect that a knowledge of its properties will be a major factor in uncovering the fundamental laws of the subatomic world? We no longer maintain such an expectation from a study of the deuteron or more massive nuclei. Why should the nucleon be more important than other nuclei? What, in other words, do we think that the nucleon <u>is</u>?

The term "elementary particle" leaps to the tongue, but after all what can such a label signify? It is easier to say what is meant by a particle"s <u>not</u> being elementary. We believe that the deuteron is not elementary because we understand many of its properties by assuming it to be a composite of two nucleons. Such a model is only approximate, and a complete understanding of the deuteron will require the inclusion of additional configurations such as $2N + \pi$, $N + \overline{N} + 2N$, etc. Nevertheless, the percentage of these additional configurations happens to be small and our first approximation does such a good job that we feel confident of the composite nature. Were the deuteron mass only 1.5 times the nucleon mass, instead of being almost exactly twice, we should perhaps not feel so confortable.

To take another example, what about the unstable particle clumsily called the "33 resonance"? A moment's thought disposes of any connection between the stability of a particle and its elementary or composite nature, but most of us are nevertheless convinced that the 33 resonance <u>is</u> composite. Why? Because its quantum numbers and its lifetime have been explained by assuming it to be a combination of other particles--in this case a pion plus a nucleon. The mass until recently had not been calculated with accuracy, but techniques are improving rapidly and seem now to be converging on an acceptable value. The most recent work is by Singh and Udgaonkar[1] and by Abers and Zemach.[2] One cannot expect high accuracy here because the percentage of configurations other than $\pi + N$ must be substantial.

What about the ρ meson? Here there is less agreement among physicists about the composite nature because neither the mass nor the lifetime has yet been convincingly calculated. Many different computational procedures, however, based on a $\pi\pi$ or a $\pi\pi + \pi\omega$ model, have given qualitatively encouraging results. I am thinking in particular of calculations by Zemach and Zachariasen,[3] by Balázs,[4] and by Burke, Morgan and Moorhouse,[5] as well as the original work by Mandelstam and me.[6] The difficulty of a relatively high percentage of additional configurations is in this case severe but perhaps not quite fatal.

The same difficulty causes many of us to be uncertain as to whether particles like the pion are composite. Here the binding energy is so great that many configurations must simultaneously be important; one cannot expect a simple model like that of Fermi and Yang, $\pi = N + \overline{N}$, to have a reasonable chance of success. There remains some tendency, therefore, to speak of the pion as "elementary", but the phrase is only an expression of ignorance. A particle ceases to be "elementary" at the moment when a convincing calculation of some of its properties is achieved on the basis of a composite model.

Well, how does the nucleon stand on such a basis? Just at present it is on the fence. There are indications that a model $N \approx \pi + N$ similar to that for the 33 resonance may in the near future give acceptable values for the nucleon mass and the pion-nucleon coupling constant.[2,7] If this happens all doubt as to the status of the nucleon will be removed. It will have to be accepted as a composite object in the same sense as the deuteron or the 33 resonance or, for that matter, the uranium nucleus. The fact that one of the nucleon components in this simplest model is itself a nucleon is an irrelevant accident stemming from the particular quantum numbers involved. The essential point is the possibility of calculating the nucleon mass and other properties on a dynamical basis.

Even if such a simple model fails, however, other criteria may be applied, of varying degrees of precision. One test, for example, involves the electromagnetic structure factors, which may be expected to approach zero for large momentum transfers if the nucleon has no central core. Indications are that the form factors do tend to vanish. Otherwise there is no obvious reason why the bulk of the isotopic vector charge and magnetic moment should reside in the configuration $N + \rho$, as is empirically observed. Were there a point core, any amount of charge could be hidden at the center. Generally speaking, the experimentally measured electromagnetic structure factors of the nucleon behave in the same fashion as those for nuclei known to be composite. There is no hint of a qualitative distinction. Later I shall come to a more definitive test of the nucleon's composite nature, based entirely on strong interactions.

I have just spoken of the circumstance that the isotopic vector electromagnetic structure of the nucleon can be understood in first approximation in terms of the $N + \rho$ configuration. What about the $\bar{N} + \pi$ combination mentioned previously? This latter configuration, so important in determining the nucleon mass, happens to be ineffective in electron-scattering experiments because of quantum-number requirements associated with the electromagnetic nature of the interaction. We must constantly remember, therefore, that different experiments probe into different components of the nucleon structure.

The term "structure", in fact, is misleading in that it may connote some kind of detailed spatial distribution of matter "inside" the nucleon. The combination of principles of relativity and quantum mechanics implies that no meaning can be attached to such a spatial distribution. What are observed in all the experiments to be discussed at this Conference (as in all other conferences on nuclear physics) are scattering amplitudes as functions of the momenta of ingoing and outgoing particles. The collection of <u>all</u> scattering amplitudes we call the S matrix, and to know the S matrix is to know all that can possibly <u>be</u> known about the subatomic world. A more accurate if less glamorous title for this Conference might be "S-Matrix Elements Involving the Nucleon." Although some of the speakers may for convenience consider Fourier transforms of scattering amplitudes and refer to the new variables as position and time, there is in fact no need to employ anything but momentum and energy in order to achieve a complete framework for analyzing the subatomic universe--including the nucleon. The existence of a subatomic space-time continuum need not and perhaps should not be assumed.

At this point some questions of language need clarification. When I have spoken of particular "configurations" in the nucleon structure the reference really has been to certain simple singularities in the relevant scattering amplitudes. Each singularity is associated through the unitarity condition on the S matrix with actual physical states, so the euphemism becomes possible. When I spoke of a possible "core" in the charge structure I really meant a behavior of the electron-proton scattering amplitude at large momentum transfers that would require a subtraction in the dispersion relation: another euphemism.

If we abandon space and time in the subatomic world, the very concept of "particle" needs re-examination. The most satisfactory statement seems simply to make a one-to-one correspondence between particles and poles of the S matrix. If a pole lies on the physical sheet the associated particle is stable, and if on an unphysical sheet the particle is unstable. The position of a pole corresponds to the mass of the particle and its residue to the coupling constant. When I spoke earlier of attempts to calculate the mass of the nucleon I might equally well have referred to the effort to locate a pole in the energy-complex plane for scattering amplitudes with $J = \frac{1}{2}$, $S = 0$, $B = 1$, etc., i.e., with the quantum numbers of the nucleon.

For future reference let me here remark that there may be an infinite number of poles for any set of quantum numbers in the strong-interaction S matrix, but most are so far from the physical region that the associated "particles" will never be identified. Roughly speaking, if a particle is to be seen its pole must be displaced from the real axis of the physical sheet by somewhat less than 1 GeV, because this displacement determines the width of the associated resonance.

The nucleon, then, is one of many poles of the S matrix. But cannot some poles be more "fundamental" than others? The Regge idea of analytic continuation in angular momentum allows one to formulate a possible distinction.* One starts with the assumption that there exists for every S-matrix element a unique continuation in total angular momentum J for Re J sufficiently large. Froissart[8] and Gribov[9] have found such a continuation for two-particle amplitudes satisfying the Mandelstam representation, and it is plausible from classical limit considerations that an analyticity domain for large J should exist in general. One also must assume that S-matrix elements can be continued from this region of large J to all physical J values $(J = 0, \frac{1}{2}, 1, \frac{3}{2} \cdots)$, but the S matrix need not be meromorphic in the entire right-half J plane, as was originally conjectured by a number of optimists. Branch points of the type discovered by Mandelstam[10] should be tolerable. Now Froissart has made it plausible that for $J = 3/2, 2, 5/2 \cdots$ the actual S matrix must coincide with its continuation from large angular momentum if

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* The most careful published discussion of this possibility is by R. Oehme, Phys. Rev. 130, 424 (1963).

unitarity is not to be violated at high energies in "crossed" channels reached by analytic continuation in linear momentum.[11] No general arguments, however, have been given that such a coincidence is required for $J = 0, \frac{1}{2}, 1$. In particular, it seems that some energy poles associated with these low J values may have an exceptional status: i.e., they may not be connected smoothly with higher angular momentum. Thus one might define an "elementary particle" of spin $\frac{1}{2}$, for example, through a discrepancy between the S matrix and its J analytic continuation at the point $J = \frac{1}{2}$. In contrast, an energy pole corresponding to a composite particle like the deuteron can be continued in angular momentum. In some cases, in fact, the pole may continue to lie sufficiently near the physical sheet real axis for several values of physical angular momentum so that families of particles can be observed.

Whether more than one member of a particular Regge family is observable depends on the strength of the attractive forces holding the composite particle together. The forces binding the deuteron are relatively weak and do not lead to detectable siblings, but those binding the nucleon and other low-mass particles like the Λ, π, and K must be very strong and the chance is correspondingly better to find at least two family members. As Rosenfeld will discuss later in this Conference, a number of possible Regge pairings have been found; furthermore, the most convincing example of a pair to date happens to include the nucleon as one member.

Circumstantial evidence, therefore, points strongly to an undistinguished composite status for the nucleon, a situation first emphasized by Blankenbecler and Goldberger.[12] This particle merely corresponds to one particular strong pole among a very large number. The quantum numbers, position, and residues of this pole are destined to be explained by the same dynamical considerations that explain all the others. I come back then to the original question. Why does this Conference concentrate on one special particle out of the vast herd? There are two excellent reasons of a practical nature, one experimental and one theoretical, and the two are related.

The experimental reason is simply that the proton is absolutely stable and the neutron has a long lifetime. S-matrix elements involving the nucleon are easier to measure than for strongly interacting particles that decay rapidly. The highest-precision observations inevitably involve particles like the proton for which beams and targets are easily arranged.

The theoretical reason is less obvious: Where ingoing and outgoing particles are highly stable, S-matrix elements tend to have a relatively simple singularity structure in the neighborhood of the physical region. Now, the only successful approximation scheme ever developed for strong interactions, where there are no small dimensionless parameters, is based on the distances of singularities from that portion of the physical region where you are attempting to make a prediction. Nearby singularities, when the Cauchy formulae (or dispersion relations as they are called in this context) are applied, turn out to be more important than distant singularities. When the close-lying singularities are simplest, the clearest predictions evidently can be made. It is therefore for S-matrix elements involving the most stable particles--such as the nucleon and the pion--that the most decisive tests of the theory are possible. This is the reason we are not so interested in the deuteron. In an absolute sense this particle is as fundamental as the proton, but human strength seems inadequate to cope with the nearby singularity structure of deuteron scattering amplitudes, beyond the no-longer-interesting part corresponding to the impulse approximation (i.e., to the 2N component of D). Proton singularities likewise become impossibly complicated if we go far from the physical region, but we know that interesting and important predictions here can be based on the nearby portions of the complex plane.

In principle <u>any</u> S-matrix element involving strongly interacting particles--even excited states of heavy nuclei--contains information as fundamental as matrix elements involving pions and protons. The difference lies only in our ability to extract this information. Such a situation, of course, is not new in physics. The hydrogen atom is no more fundamental than a protein molecule, but the crucial developments of atomic theory have been associated with the former, not the latter.

Another encouraging analogy may be drawn with atomic physics. Once one particular atom was understood it was not necessary to measure and explain the properties of other atoms in order to have confidence in one's possession of a correct and complete theory. Any one atom would have been sufficient. In the same way an understanding of enough aspects of a very few strongly interacting particles will satisfy us that the general principles are in hand. If such an understanding ever is achieved, the nucleon surely will be one of the few--for the reasons already given.

I do not want, however, to carry the analogy with atomic physics too far. There exists a crucial difference already mentioned: Strong interactions are characterized by the absence of any small dimensionless parameter that permits a clear decoupling of one particle from another. The properties of the hydrogen atom could be understood to a high accuracy without involving other atoms because of two tiny dimensionless factors, the ratio of electron mass to nuclear mass and the fine-structure constant. The proton, however, as you will see from the papers at this Conference, cannot be discussed in <u>any</u> approximation without at the same time considering <u>some</u> other strongly interacting particles. The expectation is that a finite number of these particles will suffice to give a reasonable understanding of proton properties, but we cannot expect ever to achieve theoretical calculations of a precision comparable to those of atomic physics.

On the other side of the coin, this same circumstance opens up the prospect of an eventual understanding of strong interactions deeper than ever was achieved for atoms. By this I mean that if every strongly interacting particle is a composite of others there may be no arbitrary parameters at all (except for one mass to establish the scale). By the same token the characteristic symmetries associated with strong interactions may have a dynamical origin, to be revealed at the same moment that one understands the properties of the observed particles. Theoretical papers on this theme by Cutkosky and collaborators are already appearing,[13] but I hesitate to assess for you the current degree of accomplishment. Less ambitious but related work by Capps[14] and Wong[15] has shown that there is no immediate inconsistency between a dynamical origin for strongly interacting particles and the unitary symmetry considerations of Gell-Mann[16] and Ne'eman.[17] I shall return to the general question of symmetries in a moment.

If we accept that the nucleon is just one of many equivalent strong poles of the S matrix, its study is inevitably a study of the principles of strong interactions. If we abandon the unobservable space-time continuum and restrict ourselves to the momentum-energy continuum, whose observability is limited only by the finite dimensions of the universe, what form can the subatomic physical laws assume? One essential aspect has been uncovered: the analyticity of S-matrix elements as functions of the momentum variables. Physicists seem to be of two minds about analyticity. Some find it a priori reasonable that scattering amplitudes should locally be representable by power series in the energy-angle variables. Others find this circumstance deeply mysterious and continue to seek its origin in a space-time continuum. Whatever one's point of view, however, thirty years of painstaking measurements of nuclear-scattering amplitudes overwhelmingly confirm the analyticity property. I have, of course, tacitly been assuming some kind of analyticity whenever poles have been mentioned in this lecture.

During the past year important strides have been made by theorists in the attempt to formalize a property which I like to call "maximal analyticity of the first degree." Papers by Stapp,[17] Polkinghorne,[18] Zwanziger,[19] Gunson,[20] and Olive[21] strongly suggest that a satisfactory set of axioms here is going to be achieved. Crudely speaking, the picture emerging is that, given all the energy-momentum poles of the S matrix, the analytic continuation of the unitarity condition completely determines the remaining singularity structure. All further singularities appear to be branch points whose location is prescribed in terms of the pole positions by suitable generalization of the Landau rules, the discontinuities across the associated cuts being given by recipes of the type associated with the name of Cutkosky. All poles have an equivalent status with respect to first-degree analyticity, whether on physical or unphysical sheets. No distinction is made between "elementary" and "composite" particles, and correspondingly it is expected that weak as well as strong interactions are encompassed. It is plausible although not yet proved that for elastic amplitudes with particles of high stability first-degree analyticity leads to the Mandelstam representation.

In collaboration with Frautschi I have attempted to formulate an even more potent analyticity assumption, to be applied only to strong interactions.[22] Physically this "second-degree analyticity" corresponds to the notion that all strongly interacting particles are dynamical composites of one another, associated with poles whose positions and residues cannot arbitrarily be assigned but which are consequences of

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The most satisfactory formulation of this idea to date has been achieved with the help of Mandelstam and Squires. It is simply to assert that at all physical J values, including $J = 0$, $\frac{1}{2}$, and 1, the strong-interaction S matrix must coincide with its analytic continuation in angular momentum from large J. One consequence of such a requirement is that all strong poles are Regge (composite) poles. Another is the elimination of all arbitrary constants, at least of the type introduced previously, not only pole residues and positions but also parameters not usually associated with poles, such as the so-called $\pi\pi$ coupling constant. Parenthetically I may remark that the principle of maximum strength--namely, that the Pomeranchuk-Regge trajectory saturates the Froissart limit[23]--although apparently valid and certainly of great utility, appears redundant in its content once analyticity of both first and second degree is assumed.

Anyone who has looked closely at the self-consistency requirements of the bootstrap mechanism finds it miraculous that a solution can exist at all. The degree of the miracle is reduced if, like the masses and coupling constants, the symmetries associated with strong interactions are not to be imposed independently of analyticity and unitarity but are destined to emerge as a consequence of self-consistency, as in the considerations by Cutkosky.[13] In this sense one may entertain the conjecture that <u>all</u> the observed manifestations of strong interactions, including the existence and properties of the nucleon, derive from principles of unitarity and analyticity. It may be, in other words, that the <u>only</u> possible unitary and fully analytic S matrix (not equal to the unit matrix) is the actually observed strong-interaction S matrix.

And now, the evangelism is at an end. Let us get on with our business.

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