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## CRISIS FOR THE ELEMENTARY-PARTICLE CONCEPT

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# CRISIS FOR THE ELEMENTARY-PARTICLE CONCEPT

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September 13, 1966

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It may be argued that the most consistently effective *modus operandi* in science has been the search for "elementary particles," a terminology which in this article will be used to denote any breaking down of a complex system into components which individually exhibit behavior that is simpler and easier to comprehend. No physical laws ever have been formulated that encompass all phenomena; none are perfect. Yet, through all the revolutionary changes undergone by science over the centuries a persistently successful theme survived until the nineteen thirties: Decompose the simplest system recognized and you will find simpler ones beneath.

Our purpose here is to review developments of the past three decades which suggest that the capacities of this elementary-particle idea may finally have been exhausted, without the identification of an ultimate set of primitive entities. If an end to the elementary-particle road really has been reached, science must find an alternative. One possibility will be described.

## THE DILEMMA

The elementary particle idea collided in the late twenties with a combination of the two discoveries of the century, the principles of relativity and of quantum mechanics. It was thought at first that a means for resolving the conflict would emerge, and many physicists continue even today to seek a mechanism for compatibility, but the trend of both experiment and theory is to confirm the basic nature of the contradiction.

How does the difficulty arise? In attempting to describe the situation we are faced with the semantic problem unavoidable whenever fundamental concepts are called into question: The words available to us depend for their meaning on an acceptance of principles that may be wrong. The reader, therefore, must be prepared to tolerate a low standard of precision in the argument to follow.

Roughly speaking, the combination of energy-mass equivalence from relativity and the uncertainty principle from quantum mechanics leads to the impossibility of localizing any particle within a region whose linear dimension is smaller than $\approx \hbar/Mc$, where $\hbar$ is Planck's (quantum) constant, $M$ is the particle mass and $c$ the velocity of light. Because $\hbar$ is very small and $c$ very large, this limitation is of no consequence for classical (macroscopic) physics and even ignorable for atomic physics, where the radius of the smallest atom is still about 100 times larger than $\hbar/M_{e\ell}c$, $M_{e\ell}$ being the electron mass. It is legitimate, therefore, to speak of atoms as being composed of nuclei plus electrons. For many atomic nuclei there is still a factor of ten or more between the nuclear radius and $\hbar/M_N c$, $M_N$ being the mass of an individual nucleon (neutron or proton), and so we speak of nuclei as "composed" of nucleons, but the day of reckoning was bound to come. The radius of an individual nucleon turns out to be of the same order of magnitude as the limiting size of the region within which less massive particles can be localized. Thus it becomes of dubious significance to speak of the nucleon as composed of "smaller" particles.

Even if the limit had not been reached at this particular level of structure, the problem could not indefinitely be avoided. Every step down decreases the size of the system in question and increases the minimum spatial extension of the possible constituents if, as common sense seems to demand, these become progressively less massive.

Perhaps, then, the nucleon is the final elementary particle --the end product of centuries of search. Recent experimental developments, to be described below, make such a status unlikely, but even before these experiments it was recognized that there was trouble with the idea that the nucleon should be a truly primitive object. The difficulty is common to all strongly interacting particles,[1] which as a class have been given the name "hadrons." Once again it is the combination of relativity and quantum mechanics that creates the dilemma, as we now attempt to explain.

By definition every hadron is strongly coupled to certain combinations of other hadrons. That is to say, for a hadron A there will exist transitions

$$A \rightarrow B + C + \cdots$$

for which the quantum-mechanical matrix-element is large, even though under some circumstances there may be insufficient energy for the reaction actually to proceed. The principles of relativity allow any particle to be created or destroyed, provided only that conservation of charge, angular momentum, etc. is satisfied. Thus the quantum state representing a single hadron A necessarily will contain "components" corresponding to hadron combinations, such as $B + C + \cdots$, that can have the same values as $A$ of conserved quantum numbers.

To take an example, the quantum state representing the proton contains components corresponding to a neutron plus a positive pi-meson. Also represented will be a $\Lambda$-particle plus a positive K-meson, and so on. There is an infinite number of configurations with the same quantum numbers as the proton, although the probability for a particular combination should decrease as the sum of the constituent masses increases. In any event the important fact is that estimates of matrix elements coupling various configurations to the proton shows their total probability to be so large that they control the observed physical properties of the proton.

By contrast one may hope that particles like the electron and the photon have a relatively simple description. Such non-hadrons are coupled to other systems only weakly; in consequence the notion of "elementarity" is not yet in deep trouble with the photon and the electron.

The qualms concerning the status of the nucleon raised by general principles have been reinforced by the experimental discovery of an enormous number of other hadrons, whose properties are so similar to those of the nucleon that common sense demands them to be accorded an equivalent status. There now seems almost sure to be an indefinite proliferation of such particles, the total established number increasing with time as the ingenuity of experimenters increases. In any event the currently established number of hadrons is too ridiculously large for them all to be accorded the status of "elementary."

Physicists, then, have generally abandoned the idea that any of the known hadrons is a "fundamental particle." A way of thinking so fruitful for so long, however, cannot casually be dropped, and a vigorous search goes on to find new entities which might be identified as fundamental constituents of nuclear matter. Such searching is typified by the current attention to "quarks," the momentarily fashionable candidates for such a role. No one has ever seen a quark, and there is uncertainty as to what, precisely, is meant by this term. The unsophisticated view is that quarks are particles carrying smaller units of conserved quantities (such as electric charge) than carried by ordinary hadrons--which are to be composed of quark combinations. The proton, for example, is supposed to consist of three quarks. This view, however, runs up against the general principles already discussed. In order for quarks to be tightly bound in the necessary combinations, they themselves would be coupled strongly to other particles and would thereby acquire as much structure as any hadron. Put crudely, a quark would have to be as "large" as a proton. The very nature of strong interactions precludes simplicity for any participating particle.

A more subtle attitude toward quarks is that in some sense they may be "fields" without particle manifestation. With no precedent for such a situation, however, and no consistent physical formulation of the idea, one cannot discuss it in a serious fashion. Quark fields have been formally useful in the description of certain symmetry principles for hadrons, but it is possible to describe these symmetries without speaking of quarks. The existence of hadron symmetries sheds no direct light on the existence of underlying fundamental hadronic fields.

Theories based on a few fundamental fields had been intensively discussed for decades before the introduction of quarks. Always difficulties were encountered if the fields were "local," that is, if interactions were formulated as proportional to the product of different fields at the same point of space-time. It appears that such "locality" comes into conflict with the combination of quantum and relativity principles discussed above. When the field interaction is weak, as in electromagnetism, the conflict is sufficiently remote that the theory can yield useful physical predictions. For strong interactions, however, local coupling of fields has never been formulated in an unambiguous fashion. Experience thus suggests that fundamental local-fields share the problems of elementary particles. Quark fields show no signs of being exceptional in this respect.

There has been study of non-local fields, but this approach evades the issue. A non-local field has structure for which some explanation eventually must be found. In formulating a theory of this structure,either through particles or fields, one would return to the difficulties already outlined.

## AN ALTERNATIVE

If the essential character of strong interactions in fact precludes the existence of elementary constituents, how are we to understand the system of hadrons. More and more, physicists are turning to the idea that self-consistency may be the key. Severe restrictions on the interrelationship between hadrons have become recognized during the past 15 years, restrictions connected with very general principles such as relativity and causality. It has for some time been recognized that these restrictions are so powerful that, given the existence of certain hadrons, the existence of other hadrons is required. One does not yet know how far-reaching are these constraints, but it is conceivable that <u>they admit only one set of self-consistent hadrons</u>, the set that we observe in nature.

Such a possibility has enormous philosophical attractiveness, more than the elementary particle idea, which ultimately leaves unexplained the special characteristics possessed by the basic entities. (Were quarks fundamental, for example, one would still have to understand why these objects occur in triplets and not with some other multiplicity.) The self-consistency hypothesis makes it possible to imagine that for <u>any</u> hadrons at all to exist, the entire family must co-exist in a mutually supporting framework. Such a situation has sometimes been described as a "nuclear democracy," no particle or group of particles occupying a truly central position. The mechanism of mutual support is often characterized as the "bootstrap."

Unfortunately the bootstrap problem by its very nature cannot be formulated in any mathematical framework familiar from previous physical theories because the number of degrees of freedom involved not only is infinite but in principle cannot be characterized by any <u>a priori</u> counting procedure. In fact the very concept of <u>number of degrees of freedom</u> is incompatible with the essential bootstrap idea; that is, the existence of a definite way of counting implies the existence of elementary entities. If, therefore, the bootstrap notion is to develop into a real theory, a mathematical framework heretofore unknown in physics ultimately must be introduced.

What temporary measures are being taken by bootstrap-oriented theoretical physicists to maintain forward motion during this awkward period? There are two classes of activity. The first is the study of "bootstrap models," in which the number of degrees of freedom is artificially made finite by violating certain of the general relativity-causality principles, but in which the participating hadrons are treated more or less democratically. Such models have been formulated by a variety of different techniques and have yielded the following encouraging indication: Most of the observed hadrons can be associated with the existence of strongly attractive forces in particle combinations having the same quantum numbers as the hadron in question and having a sum of masses fairly near the hadron mass. In other words one may think roughly of such a hadron as being a "bound state" of these particle combinations. For combinations where forces are weak or repulsive one generally does not observe corresponding hadrons to exist. Unavoidably there occur particle combinations so complicated that assessment of the forces becomes ambiguous, but the overall qualitative success of simple bootstrap models is impressive in dealing with the low-mass portion of the observed hadron spectrum.

The total spectrum is almost certainly infinite, however, and its artificial truncation renders bootstrap models dynamically incomplete. Arbitrary parameters are needed to represent the influence of the neglected hadrons, and it has not been possible to establish the uniqueness of the truncated spectrum.

The second approach is to study more and more deeply the implications for hadrons of generally-accepted principles of relativity and causality. A large number of constraining relations either proved or conjectured to be exact have by now been developed. Such relations inevitably involve the complete spectrum, but through expressions which have an unambiguous experimental meaning via the measurement of reaction rates. The essential point is that such rates are always described by analytic functions in which individual hadrons appear as poles.[2] Through the use of standard properties of analytic functions, therefore, the properties of individual poles are related to physically measurable quantities. (It is only through such analytic relations, in fact, that a precise definition can be given to the properties of unstable hadrons, which comprise the vast majority.) Thus constraints on reaction rates, derived from relativity and causality, imply constraints on the hadron spectrum.

There seems no limit to the number of such presumably exact constraints, and the more they are studied the more physical content emerges. Without seeing where this road is destined to lead, there is nevertheless a hope that the essential mathematical content of the bootstrap idea may be discovered through such studies. They have already led, for example, to the conjecture that all hadron poles in a nuclear democracy are connected by analytic interpolations in angular momentum, the so-called Regge trajectories. Whether such a property implies a unique overall spectrum is far from being established. It is also not known whether Regge behavior follows automatically from other and more general principles.

## THE FUTURE

It is too soon to be certain that the elementary-particle approach is exhausted and far too soon to be sure that the bootstrap idea is the track of the future. Ultimately, however, science must answer questions of "Why?", as well as "How?", and it is difficult to imagine answers that do not involve self-consistency. Why is space three-dimensional? Why are physical laws relativistically invariant? Why do physical constants have values that make it possible to understand sub-classes of natural phenomena without understanding all phenomena at once? In other words, why is science possible in the first place? The existence of science requires the concept of unambiguous measurement. Yet the feasibility of measurement depends on detailed properties of matter, such as the existence of solids and the long-range forces of electromagnetism and gravity. Matter must arrange itself in clumps sufficiently disconnected so that one clump can "observe" another. It is not even obvious that systems should necessarily exist with the necessary complexity to exhibit classical (as opposed to quantum) behavior. Without a classical limit, the notion of measurement becomes confusing--to say the least.

The bootstrap idea for hadrons does not directly touch on these profound questions but there is a similarity of spirit in concern for the notion that the laws of nature may be <u>the only possible laws</u>. Perhaps we have reached the stage where major further progress requires us for the first time to probe essential questions of self-consistency. Perhaps the hadron dilemma is the precursor of a new science, so radically different in spirit from what we have known as to be indescribable with existing language. This may turn out to be the ultimate significance of the present crisis for the elementary particle concept.

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* This work was performed under the auspices of the U. S. Atomic Energy Commission.

1. G. F. Chew, M. Gell-Mann and A. Rosenfeld, Scientific American, February 1964, p. 74. This article amplifies many of the points raised in the brief discussion here.

2. R. J. Eden, P. Landshoff, D. Olive and J. C. Polkinghorne, *The Analytic S Matrix* (Cambridge University Press, New York, 1966).