the third revolution in

20th Century Physics

By Alexander W. Stern

"Twentieth century physics already has undergone two breathtaking revolutions—in relativity and in quantum mechanics. We may be standing on the threshold of a third." Thus spoke Geoffrey F. Chew on the occasion of the Rouse Ball Lecture which he delivered at the University of Cambridge on March 12, 1963. The title of this lecture is "The Dubious Role of the Space-Time Continuum in Subatomic Physics".

In this lecture, Professor Chew eloquently, and even emotionally, expounded the philosophy of the *S*-matrix approach to the strong interactions, of which he is a leading proponent, and in the spirit of this formalism advocated discarding every concept and notion—even space-time itself—that is not directly observable.[1] The idea that only observable quantities should enter a theory was entertained by Heisenberg about 1926, when he formulated his matrix approach to quantum mechanics. He no longer dogmatically advocates such an unnatural, perhaps fatal, restriction to a theory, and now looks upon such notions more in the nature of a program rather than as the absolute conditions to which physical theories on the atomic and subatomic level must conform.

Since the war, the *S*-matrix (scattering-matrix) approach has once again become popular as a result of Heisenberg's attempt in 1943 to formulate a quantum theory without a Hamiltonian, which paper was inspired by an earlier contribution on this subject by J. A. Wheeler. Its thesis, simply stated, is that one can neglect the detailed nature of the interaction between our atomic or subatomic particles, which act as probes, and the target system. What causes the interaction, and what takes place inside the region of interaction can be neglected. One should be concerned only with the *after-effects* of the interaction, with its asymptotic, observable properties, as recorded by our apparatus infinitely far away in space and time (measured on the atomic scale) from the region of interaction. Since the interaction is considered to have taken place in the infinite past, time is no longer a significant variable with respect to the observable aspects of the interaction. Only the time sequence of observable events is maintained, a sort of counting in time, rather than time as a significant dynamical variable. Thus, any knowledge of the time development of the interaction process which gives rise to our macroscopic observations is renounced.

Because of the facility with which the *S*-matrix formalism can be applied to the strong interactions in the high-energy nuclear domain, some experts have become so enamored of its success as to wax emotional, if not eloquent. Indeed, seldom has there been so much emotion attendant upon the formulation of a new and useful, but abstract, mathematical technique as is embodied in the *S*-matrix approach to the strong interactions. This may probably be the result of the long frustrations suffered by some of the experts because they weren't getting anywhere with field theory. One such expert gallantly admits[2] that he is "quite happy to discard it as an old, but rather friendly, mistress whom I would even be willing to recognize on the street, if I should encounter her again". The leading proponent of the *S*-matrix approach to the strong interactions would not know her at all![3] However Professor Chew, in his Rouse Ball Lecture, does compare his *S*-matrix theory of strong interactions to "a mistress full of mystery, but correspondingly full of promise," and again states, "A curious facet of the new mistress, by the way, is that she can be appreciated by a far wider audience than ever was the case for quantum field theory." The author fears that Professor Chew, in his enthusiasm, may have inadvertently bestowed

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upon this new mistress an unobservable, but nevertheless an unmistakable, scarlet symbol.

Although the time is not yet ripe for a detailed prognosis of the *S*-matrix theory of strong interactions, to appraise its successes as well as define its limitations, one may, in the spirit of the *S*-matrix approach itself, exhibit some basic general features of the theory whose pathology is not promising with regard to its acceptance as a third breath-taking revolution in twentieth-century physics. This beautiful, self-consistent (even if "violently circular") formalism seems to suffer from two fundamental defects. It is incomplete, and it is basically inconsistent. Consider the case of quantum mechanics which Chew cites as one of the two breath-taking revolutions in twentieth-century physics. This theory is neither confined nor restricted only to directly observable concepts and quantities. Nevertheless, it elegantly embodies the logic of the measurement process in its formalism. This the *S*-matrix has failed to do, despite the fact that measurable quantities are at the heart of its formalism. In fact, the measurement process has no logical place in *S*-matrix theory! This fundamental inconsistency arises from the fact that the formalism does not contain, nor can one build into it, the electromagnetic field. It is inconsistent with the existence of the electromagnetic field. Because the electromagnetic field is involved in our very means of measurement and observation, this is a serious shortcoming. Also, the inconsistency of the formalism is exhibited in that it is based on abstract momentum-space—the continuum of momentum (energy) measurements—and discards the space-time continuum as unobservable. Chew compares the space-time continuum to the ether in his Rouse Ball Lecture. But measurements are made in space-time. A momentum measurement cannot be defined except through space-time measurements. So the observables in *S*-matrix theory have been reduced to abstractions isolated from the actual measuring process. But why worry how one measures quantities as long as one's measurements can be checked?

The upshot of all this, however, is that a description of nature containing only observable quantities has so little content that one does not know with any assurance or rigor whether our macroscopic measurements and observations give a complete and true picture of the phenomena. We haven't any logical connection between the scattering interaction and our observations to which they presumably give rise. The *S*-matrix theory of strong interactions cannot logically contain the weak interactions as well as the electromagnetic interactions, and it is inconsistent with the existence of their associated particles. It is thus an isolated discipline, separated from the rest of physics. It has destroyed the unity of physics, and with it, any hope of gaining an adequate and a wider and deeper knowledge of just what one is observing.

At the present time, contemporary theoretical physics in the high-energy nuclear domain may be compared to an abstract painting—features of symmetry, of arrangements and grouping, of form, rather than subject matter, are discernible. Worse yet, this painting is in an abstract, isospin space. Our knowledge in this field appears to have a disturbing triviality about it. Group and symmetry properties are employed to classify the large number of elementary particles and their interactions in their appropriate genus and species. When the mass-level spacings (i.e., mass differences between particles belonging to a particular group) can be approximately accounted for, enthusiastic letters are written to the physical journals, and when, with a little arbitrariness, one can assign the particles to their various subgroups, there follows another geyser of letters. Perhaps all this is a reflection of some new natural limitations to the acquisition of detailed knowledge in the high-energy nuclear domain, knowledge pertaining directly to events occurring in small space-time regions. Whether this is so or not can be revealed only by an adequate field theory whose theoretical structure is all the more complete and firm because of its unobservable foundations.

It is certainly nice and satisfying to have a formalism such as the *S*-matrix that is based only on a few logical principles—causality, unitarity (conservation of probability), analyticity (pertaining to the smoothness in variation of the mathematical functions representing the *S*-matrix elements as energies and angles are changed), with practically no arbitrary constants. But is it enough? Why straight-jacket physics in a circularly, logically self-consistent framework, when it is probably the most illogical of all scientific disciplines? Experience tells us that only the unexpected can be expected to occur in physics. Practically every great discovery in physics, including the two breath-taking revolutions cited by Professor Chew, has caused a revolutionary upset in man's thinking, has outraged the common sense of that time, and caused him to abandon his most cherished beliefs, ideas, concepts, and notions. The recent discovery of the violation of parity in the weak interactions surprised (to put it mildly) one of the most distinguished mathematical physicists of our time, who had wagered that the outcome of the experiment of Wu and her collaborators would show that parity is conserved. Other prominent physicists couldn't believe it when they first heard of the violation of parity. Why then accept as a credo of faith that the laws of nature follow from logical principles? Why despair of field theory when much of its structure remains to be investigated? One simply does not know a priori just what specifications a formalism must meet to be best suited for a description of nature; neither does one know what type of mathematical relationships are best realized in nature. The renormalization idea revived field theory at a time when people had even less confidence in it than they have now. Renormalization was essentially an advance in the interpretation of the theory, and permitted one to make better use of its formalism.[4] It gave physicists a new look at the theory.

A novel, important, and even dramatic idea has emerged from the *S*-matrix approach to the strong interactions. It is the hypothesis that all the strongly interacting particles may be considered as composite systems made up of one another, so that coupling constants and mass ratios can be computed. It is assumed that there are no elementary particles in the nuclear domain of the strong interactions. As an assumption regarding the origin of the elementary particles, it does not go very deep. They are considered to make their appearance by virtue of the same interaction that causes the scattering of the particles. Indeed, such a view is somewhat reminiscent of the old refrain once heard in biological circles that "life springs from life".

However, let us examine the idea from the historical and epistemological point of view. To ask whether the ultimate particles in the high-energy domain (where all interactions are strong) are elementary or composite, may be like asking whether the electron is a particle or a wave, a question asked and debated in the early days of quantum theory. As is well known, the particle-wave duality was resolved when it was realized that these concepts are idealizations. Each concept expresses the type of behavior that is predominant and significant in the particular experimental situation.[5] Analysis on the ultimate levels of nature reveals, at first, an apparent simplicity that arises out of the general mathematical principles of symmetry and group properties that are found. But as one looks a little deeper, the simplicities seem to dissolve and give way to more complex situations. Our absolutes are no longer absolute. They begin to get blurred, fuzzy, ill-defined, relative, and approximate. Elementarity and compositeness may be terms describing the types of behavior of the elementary systems in the high-energy nuclear domain rather than concepts signifying their intrinsic absolute nature and properties.

In those situations where elementary particles cannot be considered as existing apart from other elementary particles, and when they cannot be given complete and unambiguous definition as free elementary particles, they will exhibit composite behavior. It is assumed by some physicists that this new composite behavior of particles that would be regarded as elementary is a feature unique with the *S*-matrix approach, and that the elementary particles contained in conventional field theories could not exhibit such behavior. However, it has been shown[6] that a spin $\frac{1}{2}$ elementary particle in a vector-spinor field theory with a massive neutral vector boson can, under certain conditions, exhibit composite behavior as the result of radiative corrections.

This theory is, of course, not equivalent to quantum electrodynamics, since in quantum electrodynamics the mass of the neutral vector boson (the photon) is zero. Nevertheless, it does have some correspondence with quantum electrodynamics. At any rate, the implication of these studies is that the structure of field theory is rich enough so that one cannot, a priori, rule out any particular, significant form of behavior of the elementary systems from its pale. Field theory may yield a theoretical illumination and understanding of the present situation in the high-energy nuclear domain that the *S*-matrix approach cannot do because of its incompleteness as a theory. The fact that the experts are beginning to take another and deeper look at field theory may itself bring an advance which was motivated by the antifield-theory philosophy of the *S*-matrix approach. It may likely show how much there is yet that can be learned about the nature and structure of quantum field theories.

Perhaps such efforts may go beyond formal recognition of the faithful mistress that is field theory. It may even lead to a reconciliation. After all, a lady is loved for her faults, not for her perfection. Indeed, it is her faults that demand further inquiry and understanding.

Summarily, one may say that the *S*-matrix approach to the strong interactions represents an advance in computational know-how that has lifted pion physics from the inert state in which it remained for several years. It is not an advance in our understanding and knowledge of high-energy physics in the nuclear domain. This only a complete theory can give us. Physics, unlike engineering, is more than a professional activity. Physics is natural philosophy, and it is in this broader aspect that so called revolutions in physics should be judged.

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2. M. L. Goldberger, La Théorie quantique des Champs. Douzième Conseil de Physique, October 1961, p. 179.

3. Proceedings of the 1962 International Conference on High Energy Physics at CERN, p. 529. (In response to a question by Heisenberg asking, "What are the implications of the assumption that Regge poles exist and no other kind of poles to field theory?", Professor Chew replied, "I really do not understand field theory well enough to have a reliable opinion on this question." The Regge-pole concept is embodied in the formalism of the *S*-matrix of the strong interactions. It is a mathematical concept that represents a single-particle state of a non-elementary particle. Regge poles are important because they are assumed to determine the asymptotic behavior of the *S*-matrix.)

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