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Scattering of extended hadrons and time-reversal invariance

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An unconventional description of scattering of extended hadrons is proposed which could shed some light on the meaning of the recently published data indicating a violation of the time-reversal invariance of nuclear reactions.

In spite of the great progress achieved in studies of quark gluon dynamics in the framework of *QCD*, we are still far from a main goal, which is a dynamical theory able to describe hadron-hadron scattering quantitatively.

Studies of extended objects such as solitons,[1,2] bags,[3] and string[4] have intensified recently. However, it has not generally been realized that a picture of really extended objects can have serious implications for the description of their scattering, such as violation of the optical theorem or of time reversal invariance. One exception to this statement is the nonstandard analysis of the strong interactions called hadronic mechanics, developed recently by Santilli, Mignani, and Eder *et al.*,[5] which predicts a violation of *T*-symmetry in nuclear physics. This violation was observed by Slobodrian *et al.*[6] and Pouliot *et al.*[7] in polarization-analyzing-power experiments.

In 1975 we wrote an article, which appeared only as a preprint (Warsaw University IFT/75/19), containing in our opinion some relevant remarks concerning the scattering of extended hadrons. Encouraged by the experimental results mentioned above, we reproduce the reasoning of this preprint without any major changes.

The existing quantum theory (QT) is in fact a theory of pointlike objects. It is a completely successful theory for the description of the phenomena of atomic, molecular, and solid-state physics down to distances of the order 10^{-8} cm. However, everybody is aware of the fact that it may fail to describe the interactions of the elementary particles at distances of order 10^{-13} cm or less. At these distances the pointlike approximation may break down, and a completely new theory may be needed.

The idea that the elementary particles should be treated as really extended objects is a very old one. The first attempts to treat electrons as extended objects were due to Abraham and Lorentz. Since that time, different models of the very high-energy scattering of extended hadrons have been proposed and investigated by Heisenberg, Fermi, Landau, Hagedorn, Carruthers, and many others.[8]

Recently, ambitious models of really extended hadrons have been proposed by Chodos, Jaffe, Johnson, Thorn, and Weisskopf[9]; nowadays they are called MIT bag models. A size of the hadron in this model is not a new parameter, but is strictly connected with the hadron's inertial mass.

In this paper we want to give some additional heuristic arguments in favor of the extended models of hadrons and to propose a general scheme for the description of the scattering of such extended particles. The proposed scheme has serious model-independent implications which can be tested experimentally.

Let us consider the following two examples:

Example A. A rocket is approaching the earth. If it is far enough away, both the rocket and the earth can be treated as material points, and the motion is given as a solution of Newton's equations.[10] As the rocket approaches the earth more closely, the earth cannot be treated as a material point, but the rocket's motion still can be described with the help of Newton's equations. However, if the rocket hits the earth, making a big hole, the classical point mechanics is completely unable to describe this phenomenon.

Example B. Let us imagine the scattering of the negatively charged small mercury droplets on the air pillow. As long as the droplets move not too fast and the Coulomb repulsion is strong enough to prevent them from touching each other, the conventional classical description and the pointlike ap-

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proximation work perfectly. If the droplets start to hit each other, a completely new approach is needed to explain the observed variety of phenomena.

A natural hypothesis to put forward is that the hadrons are really extended objects and that the pointlike approximation, completely correct in atomic physics, breaks down slightly in the nuclear physics and completely for strong-interaction scattering (SIS). In nuclear physics hadrons can perhaps be treated as nonpointlike sources of some strong short-range forces (SF). In contrast to the SF, the forces which keep the hadron's matter together and which are important for the high-energy inelastic SIS we call superstrong forces (SSF). The SF seem to be mainly responsible for the elastic SIS. Presumably, it is the interplay of these two types of forces that makes the experimental picture of the high energy SIS so complicated. It seems to us plausible to assume that the extended hadrons have two radii: a superstrong radius R_1 and an effective strong radius R_2. The existence of these radii suggests that the final states which may appear in the collision of the two extended hadrons should depend on the quantum numbers of the two-particle system which give information about the spatial separation of the particles in the system, such as the impact parameter b or the relative orbital angular momentum L. Thus, an event called a strong interaction (for the spherically symmetric hadrons C and D) occurs if $R_1^C + R_1^D \le b \le R_2^C + R_2^D$. A superstrong interaction occurs if $0 \le b \le R_1^C + R_1^D$. It may seem strange that we use the quantum numbers of a two-particle system though we claim that the conventional QT is unable to give the description of the SIS. However, one has to take into account that the QT is a correct theory for the description of the time evolution of the physical microsystems before and after the strong interaction took place. Similarly, in the Examples A and B above, Newton's equations had to be used to calculate the time and the place of the catastrophe (the inelastic scattering event).

Therefore a plausible model for the description of the SIS consistent with the QT seems to be the following. In the usual preparation of the beams and the targets the extendedness of the hadrons is not important. Thus the initial two-particle state can be described by the conventional state vector $|i\rangle$ in the Fock-type Hilbert space H. Due to our hypothesis, this description has to break down and the final state of the SIS event has to depend on the values of the quantum numbers characterizing a *particular pair* of the colliding particles. A set of these quantum numbers are denoted by μ. *A priori* one might assume that μ is a complete set of quantum numbers containing the relative angular momentum L.[11] However, this choice is not consistent with the data, and one should rather take a set containing the impact parameter b. Due to the two-radius structure of the hadrons here assumed, the set of the values of μ divides into three disjoint subsets A_1, A_2, and A_3. For $\mu \in A_1$ the states do not interact strongly, for $\mu \in A_2$ they only interact strongly, and for $\mu \in A_3$ they only interact superstrongly. The details of the SIS can depend on the particular values of $\mu \in A_2 \cup A_3$. Thus the following picture emerges. The probability p_{if} for finding as the result of SIS a final state $|f\rangle$ is given by the formula

$$P_{if} = \sum_{\mu} P_{\mu f} |\langle \mu | i \rangle|^2, \qquad (1)$$

where $|\mu\rangle$ and $|f\rangle$ denote quantum eigenvectors associated with the quantum numbers μ and f respectively, and $P_{\mu f}$ denotes the corresponding transition probabilities. If $\mu \in A_1$, the probabilities $P_{\mu f} = \delta_{\mu f}$. If $\mu \in A_2 \cup A_3$, the $P_{\mu f}$ have to be calculated by a new theory of the SIS. In this new theory the hadronic states have to be represented by a pair (μ, ξ), where ξ denotes a set of the new variables characterizing the inside of the hadron. A dynamical model[12] has to describe the transitions $(\mu, \xi) \to (f, \xi')$. The description of these transitions can be hydrodynamical, quantum field-theoretical, or other. In the quantized MIT bag model the confined colored quarks can interact via the exchanges of the confined colored Yang-Mills gluons.[9,13]

The formula (1) for the P_{if} has the following important implications independent of any particular dynamical model used for the calculation of the $P_{\mu f}$:

1. The new dynamical model for the SIS has to be used for the calculation of the *probabilities*, not of the cross sections.
2. The true total (strong) cross sections are simply *geometrical* ones: $\sigma_{\text{tot}}^{\text{true}} = \sigma = \text{const.}$
3. The measured total cross-sections σ_m depend on the energy according to the relation

$$\sigma_m = \sum_{f'} \tilde{P}_{if} \sigma, \qquad (2)$$

where $\tilde{P}_{if}$ is a relative probability for finding the experimentally distinguishable final state $|f'\rangle$ if the initial state was $|i\rangle$ and if the strong interaction took place. $\tilde{P}_{if}$ is defined by the formula

$$\tilde{P}_{if'} = \frac{\sum_{\mu \in A_2 \cup A_3} P_{\mu f'} |\langle \mu | i \rangle|^2}{\sum_{\mu \in A_2 \cup A_3} |\langle \mu | i \rangle|^2} . \tag{3}$$

4. The initial ensemble of two-particle states behaves as a *statistical mixture* of the pure two-particle states characterized by the quantum numbers μ.
5. The probabilities for the free motion and for the forward strong elastic scattering add incoherently; thus one cannot prove the optical theorem in this scheme.

The importance of points 1 and 2 has been recognized by Fermi.[14]

The formula (1) and point 4 are also consistent with the interpretation of the SIS as a two-step process. The first step is a self-measurement of the set of quantum numbers μ which changes a pure state $|i\rangle$ into the mixture, and then the independent time evolution of the corresponding pure components takes place.

One might say that point 5 alone is enough to kill the description of SIS proposed above, because the validity of the optical theorem is strongly confirmed by experiment. That is not true, however, since in fact the optical theorem is an untestable one. One can only check its consistency with a whole set of the assumptions adopted for the extrapolations to the forward direction or with some theoretical phenomenological models. We don't have the proof that the breakdown of the optical theorem cannot be also made consistent with the experimental data. Moreover, the optical theorem, believed to be the unquestionable truth, has been a strong bias in any experimental analysis. Recently it has been pointed out[15] that due to some particular impurity of the initial states (intuitively, connected with extendedness of the hadrons) one can have the unitary S-matrix description of the SIS without being able to prove the optical theorem. The need for testing the optical theorem has been also pointed out in a different context by Bell and Eberhard.[16] Data seeming to violate the optical theorem exist,[17,18] but they can be always explained by the incorrectness of the extrapolation procedure. Therefore any direct test of the optical theorem is highly inconclusive. On the contrary, the impurity of the initial states of the type mentioned in point 4 should reveal itself in experiments. Simple purity tests have been recently proposed.[19] We believe that such tests may give model-independent support for the fascinating idea of extended hadrons.

In conclusion, we would like to mention that if hadrons are really extended objects, one can also expect that the usual procedure of obtaining a time-reversed state by changing the directions of the linear momenta and rotating the spins is not a sufficient one. Therefore, it would not be surprising if experiments with polarized proton beams, which have already led to some unexpected results,[20] were to show a violation of the "conventional" time-reversal invariance.[21]

This ends the 1975 paper. We would like to add two explicative remarks. In the proposed description one has to use quantum mechanics or quantum electrodynamics to calculate the probabilities of finding of the extended hadrons in a particular (μ, ξ) state. If one wants to describe the subsequent strong interactions giving the transition $(\mu, \xi) \rightarrow (f, \xi')$ with the use of quantum field-theoretical methods, the S-matrix elements should be normalized (if possible) to give the probabilities of the various results—not the cross sections as in the usual approach.

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