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Research Accomplishments of the Indiana University
Theoretical Particle Physics Program*

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We briefly describe in terms the educated layman can understand the significance of our theoretical research in elementary particle physics.

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I. Do Any Elementary Particles Have Color and Charm?

The principal constituents of ordinary atomic nuclei appear to be protons and neutrons. But protons and neutrons are only two of a large class of elementary particles called hadrons, most of which have been discovered since 1947. Most of these hadrons are highly unstable, with lifetimes much less than a millionth of a second. They are created in high-energy collisions of protons with atomic nuclei, and then decay radioactively into other particles.

The hadrons have one common property - they all interact strongly with one another. This means that all the hadrons must play some role, as yet not clearly understood, in the strong forces that bind protons and neutrons together to form nuclei. Thus, a real understanding of nuclear forces will depend upon an understanding of the properties of hadrons.

As yet, however, we do not even know how many hadrons there are. Hundreds have already been discovered, and more continue to be discovered every year. Because there are so many different kinds of hadrons, it is tempting to regard them as composite particles made of something simpler.*

In 1964 Gell-Mann and Zweig independently proposed that hadrons are composites of simpler entities, which Gell-Mann called "quarks". To this day, quarks have not been discovered, and it is not known whether quarks exist or not. It is however, very useful to regard hadrons as being made of quarks independently of whether quarks will ever be observed. The reason is that use of quark model of hadrons allows one to make many predictions about the properties of hadrons, most of which have been approximately verified by experiment.

* We still retain the name "elementary particle" for a hadron even though we regard it as composite rather than elementary, just as we retain the word "atom", which means "indivisible", although atom smashers exist.

How many different kinds of quarks are needed as building blocks for the hadrons? Originally, Gell-Mann and Zweig suggested that there are three, two to allow the proton and neutron to have different electric charges, and a third to carry a property known as "strangeness", so that the so-called strange hadrons could also be built up out of quarks. An interesting property of the quarks is that they are supposed to have fractional electric charge -- that is, electric charge smaller than the charge on the electron, which is the smallest charge observed so far in nature.

Shortly after Gell-Mann and Zweig proposed the quark model, several modifications were made. Greenberg proposed that quarks did not obey the same statistical laws as ordinary particles. Later, Greenberg, as well as a number of other people including Gell-Mann and one of us (Lichtenberg), showed that Greenberg's idea was equivalent to introducing a new property for quarks, arbitrarily called "color". Each of the three kinds of quarks is supposed to come in three different colors, and so there should be nine quarks in all. At around the same time, Han and Nambu proposed an alternative model with nine quarks, which have integral charges. The Han-Nambu quarks also come in three colors.

Another modification in the model was made by Bjorken and Glashow, who proposed that a fourth kind of quark should exist carrying a property they called "charm". If this fourth quark exists, and if each quark comes in three colors, there are altogether 12 quarks.

The properties of color and charm, which the quarks are assumed to have, may also be properties of some hadrons. Certain recent discoveries make this idea more attractive, as we shall now discuss.

In November of 1974, the discovery of a new kind of particle was announced at Brookhaven National Laboratory and at the Stanford Linear Accelerator

Center. This particle, called J at Brookhaven and ψ at Stanford, appears to have many of the properties of hadrons, and we are of the opinion that it is in fact a hadron. It is a heavy particle, having a mass more than three times the mass of the proton. Now ordinarily, very heavy hadrons are highly unstable, decaying with very short lifetimes into lighter hadrons. The $J\psi$, on the other hand, lives about a thousand times longer than expected for such a heavy hadron.

Numerous possible explanations were at once put forth by many physicists to explain the peculiarly long lifetime of the new particle. One suggested explanation is that the particle has color. If so, it would be the first colored particle to be observed in nature.

Another suggested explanation, proposed independently by many physicists including one of us (Lichtenberg), is that the new particle provides indirect evidence for the existence of charm. According to this idea, the new particle does not itself have charm, but is a composite of a charmed quark and its antiparticle, a charmed antiquark. According to the model, the antiquark has negative charm, and this cancels out the positive charm of the quark, so that the new particle has zero net charm.

But if this explanation is correct, we can use the quark model to predict the existence of a family of other hadrons which have net charm different from zero. These hadrons, which have not yet been observed in nature, are supposed to be composites of both charmed and uncharmed quarks, so that the net charm does not cancel.

It is all very well to make theoretical predictions of the existence of new elementary particles with unusual properties, but it is quite another thing to observe them in the laboratory. Any clue we can provide about the properties of charmed hadrons will help the experimental physicist in his

search for them. One of the most important and fundamental properties of an elementary particle is its mass. If we can tell the experimentalist at what mass he is likely to find charmed hadrons, we will make his search for them considerably easier.

Two of us (Hendry and Lichtenberg) have used the quark model to make predictions of the masses of charmed hadrons. The methods we used were quite simple, relying principally on the assumption that the masses of hadrons depend in a straight-forward way on the masses of the quarks out of which they are composed. We also made small corrections to the hadron masses to take into account the differences in forces among the different kinds of quarks.

According to our predictions, the lightest charmed hadrons have masses about twice the mass of the proton. Furthermore, heavier charmed hadrons should exist with masses up to about five times the proton mass. We have a certain amount of confidence in our predictions because our methods also enabled us to calculate the masses of observed uncharmed hadrons, and we found rather good agreement with the measured masses. We look forward to the time when experimental physicists will discover particles having charm with masses near the values we have predicted.

II. Scattering of Elementary Particles

The problem of the nature of the strong forces between hadrons is one of the most central to the field. A knowledge of these forces is necessary for us to be able to really understand nuclear physics as we now understand atomic physics.

One of the chief barriers to obtaining information about the forces between hadrons is their short range. The interaction between two hadrons is very strong at separation distances of the order of the size of an atomic nucleus, but the interaction rapidly becomes negligibly weak at appreciably longer distances. Because the interaction distance between hadrons is so small (less than a trillionth of a centimeter), we cannot measure the forces between hadrons directly. Instead, a variety of indirect measurements are made, which yield clues as to the nature of the forces. One of the most important ways to obtain indirect information about the forces is by scattering experiments. Typically, a high-energy beam of hadrons is directed at a nuclear target and the scattered particles are counted at various angles away from the beam direction.

We have devoted a large part of our time to interpreting the results of scattering experiments at high energy. We have been concerned with scattering of some of the most fundamental particles, namely beams of protons from proton targets and beams of pions^{*} from proton targets. The reason for being interested in high-energy scattering is that beams of high energy can penetrate

* The pion is the meson predicted to exist by Yukawa, who suggested that it is responsible for nuclear forces. We now know that Yukawa's ideas were only partially correct. Although the pion contributes to nuclear forces, so do many other hadrons.

deeply into the interior of the nuclear target and give us information about the nature of forces at small distances.

In the absence of a complete theory of the interactions of hadrons, we construct simple models which we hope will contain some of the features a future true theory will have. We calculate the expected scattering according to these models, and then compare our calculations with the experimental results. Typically, the agreement between one of our models and experiment is pretty good, but not perfect. We then try to improve and refine our model so as to get better agreement with the existing experimental data. In the meantime, additional experiments are done, and provide the improved model with further tests. In this way, with the interplay between experiment and theory, we hope to learn more and more about the nature of the forces between hadrons.

The models we are considering are of two kinds. In the first model, we regard the target as a partially opaque body, which both absorbs and scatters some of the particles in the beam just like a translucent disc absorbs and scatters part of the light passing through it. Because of the close analogy in this picture between the absorption and scattering of light and particles, this model is called the "optical model".

The second model ascribes the forces between hadrons to the exchange of other hadrons between them. In its original form, this model dates from Yukawa who regarded pions as the exchanged particles. However, the model has been improved by allowing the exchange of hadrons other than pions, and by modifying the properties of the exchanged particles according to the ideas of Regge. This model is called the "Regge exchange model".

It may appear that the optical model and Regge exchange model are two entirely different ways of describing scattering processes. But the models may in reality be two complementary ways of looking at the same thing. It

is an interesting field of research to try to understand the relation between these two models. Two of us (Chu and Hendry) have devoted some effort to exploring different aspects of this relationship, and have had some success.

But for the most part, we have been pragmatic in our approach, using whichever of the two models we believe can describe a given physical process most simply.

Two of us (Chu and Hendry) have applied the optical model to the scattering of pions by protons and protons by protons. We have been quite successful in interpreting the main features of the experimental data in terms of the model. If the number of scattered particles is counted at different scattering angles, the experiments show that definite maxima and minima occur, just as for light. By adjusting several parameters of the model, we are able to obtain good agreement with experiment over the entire range of angles of scattering.

Another phenomena that occurs with light is that scattered light is often partially polarized. This same phenomena also occurs when particles are scattered. An extremely important success of our optical model is that we have been able to predict how the polarization of scattered particles varies with angle.

One of us (Lichtenberg) with collaborators Shtokhamer and Heinz has also looked at proton-proton collisions from the Regge exchange picture. In this case, we considered not an ordinary scattering process, but collisions in which the two protons are destroyed and a pion and a deuteron^{*} are created. We were able to obtain good agreement with experiment for the number of created particles, but not such good agreement with experiment for the

* A deuteron is a nucleus of heavy hydrogen.

polarization. This is a case where a disagreement between a model and experiment provides clues for improving the model.

In conclusion, we have applied two different models (the optical and Regge models) to the scattering of hadrons at high energy. We have had good success with these models, and thereby have obtained important information about the nature of the fundamental strong forces in nuclei.