

Mesons and Nuclear Forces

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By *Hans A. Bethe*



Hans A. Bethe is professor of physics at Cornell University. Born and educated in Germany, Professor Bethe received his PhD at Munich in 1928 and taught physics at Frankfurt, Stuttgart, Munich, and Tuebingen before leaving Germany in 1933 to go to Manchester University in England. In 1935 he came to the United States as associate professor at Cornell. In 1942-43 he was a staff member of the MIT Radiation Laboratory, and from 1943 until the end of the war he headed the theoretical physics division at Los Alamos.

THE HISTORY of the subject of mesons and nuclear forces is an example, as good as any I know in recent scientific progress, of both the wisdom and the folly of scientists. The theory of nuclear forces began in 1932 with the discovery of the neutron. This made possible a consistent picture of the structure of the nucleus, namely, to consider the nucleus as composed of neutrons and protons which are held together by very strong forces, different from and stronger than any other forces which we had known in nature before. Only three years after the discovery of the neutron and the start of nuclear theory, Yukawa suggested that the nuclear forces were transmitted between the nuclear particles, the neutron and the proton, by other particles as yet undiscovered, which have now come to be known by the name of mesons. Yukawa predicted that there should be such particles, that they should have a mass of 100 to 200 times the electron mass, that they should be charged, and that they should have integral spin, probably either zero or one.

Three years later, Yukawa's prediction came true. Particles were discovered in cosmic radiation by two groups of people, Anderson and Neddermeyer, working at the California Institute of Technology, and Street and Stevenson, working at Harvard University. These particles had a mass of about 200 electron masses, they had a positive or a negative charge just as Yukawa had wanted, and they seemed to fulfill pretty well his program. In the succeeding nine years experimental physicists kept discovering more and more properties of these particles and theoretical physicists kept calculating what such particles would do for nuclear forces.

Only the twain never met; the predictions of the theorists were completely different from the way the particles actually behaved.

The theorists predicted that these particles, the mesons, should interact very strongly with nucleons once they were formed and should, therefore, be easily absorbed, be easily scattered, and should easily cause nuclear reactions. They did nothing of the kind. In fact, they did nothing of any kind. They just moved along, were slowed down as any charged particle is, finally came to a stop and disintegrated in some way then unknown. All the same, theoretical physicists persisted in their belief in the connection between Anderson's cosmic-ray particle and Yukawa's prediction. But the differences between the experimental results and the theoretical prediction were so great that it was proposed to make the best of another disagreement among physicists, one about the name of the particle, and to call the experimental particle, the mesotron, and the theoretical particle, the meson. Attempts to identify the two particles continued until finally, in 1947, a group of Italian physicists, Conversi, Piccioni, and Pancini, found that the cosmic-ray meson had even less interaction with the nucleus than had been suspected before. Even when they gave the meson a chance of sitting around the nucleus for a long, long time, namely a microsecond, even then it wouldn't make use of its opportunity and would not get captured by the nucleus. This finally proved that the two particles could not be identified. But then it took only a few months before the solution to the puzzle was found in Bristol, England, by Occhialini, Powell, and Lattes, who discovered that there existed still another particle which they called the π -meson, the primary meson, which decayed after a short time into the meson which had been previously discovered and which they called the μ -meson, the "meson" meson.

The π -meson, at last, fulfilled Yukawa's dream. It had a strong interaction with the nucleus. Once created, it was easily scattered; it was easily absorbed by the nucleus; and since 1947 we have come to believe that the π -meson really is the particle which transmits nuclear forces. Many properties of the π -meson were discovered by the Bristol group, working with cosmic-ray mesons and photographic plates, but the greatest progress about finding out the properties of this particle was only made after this particle was produced artificially in accelerators, first at Berkeley, then also at other laboratories. This again was an example of international cooperation: a powerful synchro-cyclotron was available in Berkeley, but the Berkeley physicists did not discover artificially produced π -mesons until the special technique of reading photographic plates was brought to them from England by a Brazilian, Lattes. Since that time we have learned quite a lot about π -mesons and this is what I want to talk about. However, before the main subject, it will be good to review some of the properties which had been predicted for the π -meson by nuclear physics on the basis of pure theory.

Predictions from Nuclear Physics

In the first place, from nuclear physics it was predicted that the meson transmitting nuclear forces should exist in three forms, positively charged, negatively charged, and neutral. The positive and negative varieties are easily visible. The neutral variety was only a theoretical prediction until 1949, based upon a very fundamental property of nuclear forces, namely, the so-called charge-independence. In 1935, it was discovered in the Department of Terrestrial Magnetism of the Carnegie Institution in Washington that the forces between two protons are just about the same as the forces between proton and neutron provided the particles are in the same state of motion with respect to each other. This fact has, in the meantime, been established by many other pieces of experimental evidence, and by the theoretical work of Breit and others, and is known as the theorem of charge independence. Now if there were only charged mesons then there could only be processes of the type that Yukawa had predicted, namely, the following: A proton can emit a positive meson, thereby turning into a neutron, and the positive meson can then be absorbed by some neutron which may be in the neighborhood and which thereby is changed into a proton. A second proton in the neighborhood could not absorb the positive meson because thereby it would acquire two charges and that would give a particle which presumably does not exist. So in this way we can have an interaction between a proton and a neutron, but not between two protons. When proton and neutron interact, they exchange their charge, a kind of interaction which had been postulated in nuclear physics even before Yukawa and was known as exchange force. In fact the exchange character of the forces was one of the clues which Yukawa had when he invented his theory. However, you can see that by the exchange of charged mesons you cannot, in first order, get any interaction between two protons or between two neutrons; you need a neutral particle in order to transmit such interaction. That a neutral meson should exist was first postulated by Kemmer in England who set up a theory known as the "symmetric meson" theory. In this theory, neutral and charged mesons of either charge are all presumed to be coupled to the nucleon, and the strength of the coupling is supposed to be the same for all. (The proton and the neutron are both called by the generic name "nucleon".) Kemmer's theory leads indeed to charge-independence of nuclear forces.

After physicists were able to produce mesons artificially they found, in fact, the neutral meson in addition to the charged mesons. The neutral meson unfortunately cannot be seen directly because it has an extremely short life. It decays within something like 10^{-15} seconds into two gamma rays. The short lifetime can be understood theoretically but I will not go into this problem.

A second point which nuclear theory predicted about mesons was that the mesons should not be scalar; a

scalar particle is one which has no spin, in contrast to electrons and nucleons which have a spin of one-half—i.e., they have an angular momentum “around their own axis”, somewhat like a spinning top. The term “scalar” implies more than the absence of spin; it also implies that the wave function of the particle remains unchanged when the entire space is reflected on a mirror plane. There is also the possibility that the wave function of a spin-zero particle changes sign upon such reflection; in this case, the particle is called “pseudoscalar”. Now scalar mesons could be excluded because the nuclear forces resulting from them are central forces depending on the separation of the two nucleons and on nothing else, whereas experimentally the forces are found to depend also on the direction of the spins of the two nucleons. The third prediction of nuclear theory was that the mesons should be pseudoscalar. This was deduced, in fact, from the detailed dependence of nuclear forces on the direction of the nucleon spins, in particular from the sign of the quadrupole moment of the deuteron.

A fourth prediction comes from an entirely different field of physics—not from nuclear physics but from an investigation of the fundamental properties of fields which has been pursued with some success, especially since 1947. The problem is the mathematical treatment of the interaction of two fields like the electric field, the field of mesons, of nucleons, of electrons, etc. Before 1947, the treatment of such interactions gave certain infinite results, but since 1947 we do know how to deal with these infinities. This is done by the so-called “theory of renormalization” in which the quantities which used to turn out infinite are re-interpreted as a change of the mass and the charge of the particle. After such re-interpretation, one can then show that all physically observable quantities are, in fact, finite. This modern theory of fields is further able to tell the sheep from the goats: certain theories *can* be made finite by renormalization, whereas others are intractable. You can write the fundamental equations of these other theories on paper, but when you try to calculate the probability of—let’s say—the scattering of a meson by a nucleon, you will invariably find an infinite result. So this development of the theory of fields has given us a principle of selecting between possible and impossible expressions for fields and their interactions. In particular, a field consisting of charged particles, like mesons, which can be emitted, and absorbed by other charged particles (nucleons), can only have spin zero. So in this respect the theory of fields confirms what nuclear physics had already postulated, namely, that mesons should have spin zero. And it said one more thing, about the coupling of the mesons with the nucleons, which I will discuss later.

Properties of Free Mesons

Now let us examine the experiments on mesons. There are many types of experiments that you can do with particles. The type of experiment which I shall

discuss first is a simple one, which can be interpreted without elaborate calculations—just the qualitative result is sufficient to give an answer. First of all, the mass of the meson has been very accurately determined; it is 276 electron masses for the charged meson and 265 for the neutral meson. The difference may perhaps be due to an electric self-energy, i.e., due to the interaction of the electric charge of the charged meson with the electric field. Secondly, we know that the mesons have only a finite lifetime; the charged π -mesons live about 10^{-8} seconds. This is relatively long and makes it possible to observe them because, if you have a charged meson of this lifetime moving with a velocity close to that of light, then it will on the average go 10 feet before it decays, which is a sufficient distance to make observations. On the other hand, the neutral meson which lives for 10^{-16} seconds will travel only about 10^{-5} centimeters, which isn’t enough to observe its properties before decay. The third property, which is a much more important one for our consideration, is the spin of the particle. This has been determined experimentally for both the charged and the neutral meson, by methods which are both ingenious and quite different.

The determination for the charged meson is based upon the statistical principle of detailed balancing. One knows from statistical mechanics and from quantum mechanics that when you have a process which can go in one direction and then a process which can go the opposite way, the probabilities of these two processes must bear a close relation to each other. Namely, if all the types of particles involved were present at a very high temperature, such that there were equally many particles in each quantum state, then processes in both directions must occur equally often to preserve equilibrium. Now, what does this principle of detailed balancing have to do with the spin of the meson? If you have a particle of spin zero, and if this particle is in an external field, then there is only one way for this particle to behave: it can’t orient anything with regard to the external field; it has only one quantum state. On the other hand, a particle of spin one can have three different orientations of its spin with regard to the external field. Now, let us consider a process in which a spin-one meson is produced and a process in which it is absorbed. If it is produced, it can be produced with three different directions of the spin. If it is absorbed, we know that it starts out with one definite direction of spin; therefore the ratio of the probabilities of being produced and being absorbed will contain a factor three if the particle has spin one, a factor which is known as the “statistical weight”. If the particle has spin zero, on the other hand, the factor three is replaced by one, so that the ratio of production probability to absorption probability is three times smaller. This principle was suggested by Marshak for the investigation of the meson spin and was used successfully by two groups of experimental physicists, one at the University of Rochester and one at Columbia University. Both came out with the result that the meson,

indeed, has spin zero as had been predicted by both nuclear physics and the general theory of fields.

A little more difficult was the next step, namely, to find out whether the meson is scalar or pseudoscalar; and now I must explain in more detail what this means. You probably know that atomic systems are characterized by a certain quantity which is known as the *parity*. The parity tells you how the wave function of the system behaves when you change the sign of all the coordinates, that is, when you change x into $-x$, y into $-y$, z into $-z$, i.e., when you make what is known as an inversion. In the case of zero angular momentum, you can do something simpler instead, namely, take a plane through the center of the atom and make a reflection of the whole space on this plane as if the plane were a mirror. Now let us ask what the wave function does when you make an inversion. We know that there are atomic states whose wave function does not change; we call these "even". There are other states whose wave function changes sign upon inversion, those we call "odd" states. This is the property that we call the parity. For instance, in optical spectra, any allowed spectral line leads from an even state of the atom to an odd state, or *vice versa*. Similarly, one defines the parity of nuclei. For instance, the deuteron consists of a neutron and a proton with a wave function which is even. At the same time the deuteron has an angular momentum of one, which comes from the spin of the nucleons being parallel, so we have an even state of spin one. Now suppose the deuteron is made to absorb a positive meson, then it will change into two protons. These two protons obey the Pauli principle, which says that the wave function of the whole system must be antisymmetrical, and which, therefore, says that there must be a certain relation between the spin of the system and the parity. It says, among other things, that it isn't possible to have any state of spin one and even parity but only of spin one and odd parity. This conclusion from the general principle of quantum mechanics is somewhat complicated to derive so I won't bother to do it.

Now, the way that the parity of the meson was determined was exactly by an experiment in which mesons were absorbed by a deuteron. To start with, negative mesons were allowed to be captured in a Bohr orbit around the deuteron. When this happens, the meson will finally go into the innermost Bohr orbit which has zero orbital momentum and afterwards, if you wait long enough, it will be captured by the deuteron. Since it has negative charge, the meson will convert the deuteron into two neutrons which will then leave in opposite directions. Then one can ask whether this capture process is permitted by conservation laws. Now, as I said, the charged meson has no angular momentum to contribute; so you start out with an angular momentum of one and with a state of even parity of the deuteron. Then in the end you get two neutrons, and as I have just said about two protons, so also two neutrons cannot exist in a state of angular momentum one and even parity. Therefore, this process ought to

be forbidden by the rule of parity conservation and angular momentum conservation—unless the meson itself contributes something to the parity. But actually, experimentally, the capture of negative mesons by deuterons occurs with great eagerness, and it does give two neutrons. So we have to conclude that the meson contributes something to the parity, that it changes the parity of the system. This is precisely what is meant by a pseudoscalar particle; it is one which changes the parity of the nucleon system when it gets absorbed or emitted by the system.

Coupling of Mesons and Nucleons

Therefore, up to this point, the experiments had confirmed exactly what the theory of nuclear forces had predicted. Now the next point is a considerably more difficult one and is perhaps the most important question in meson theory. This is the question of *how* the mesons are coupled to the nucleon. The coupling of mesons—the coupling of any two fields—is expressed by a term in the Hamiltonian of the system, and I am afraid I have to get a little bit technical at this point. The expression for the interaction will contain the two interacting fields. Now the meson is described by a wave function which I shall call ϕ ; the nucleon wave function shall be called ψ ; and the so-called adjoint wave function of the nucleon shall be $\bar{\psi}$. The coupling with a pseudoscalar meson will further contain the Dirac operator known as γ_5 —which is a very recondite thing. The two expressions for the coupling which have been most used are then:

$$(1) G\bar{\psi}\gamma_5\psi\phi \quad \text{direct or pseudoscalar coupling}$$

$$(2) g\bar{\psi}\gamma_5\gamma_\mu\psi\frac{\partial\phi}{\partial x_\mu} \quad \text{pseudovector coupling}$$

The first of these is known as "direct" coupling; it contains the meson wave function itself. The second type of coupling which was almost exclusively used in the literature until 1947 contains the derivative of the wave function of the meson with regard to the coordinates; it also contains some of the more ordinary Dirac operators, γ_μ , where μ runs from one to four. These two couplings are also known as the pseudoscalar and the pseudovector couplings.

Now the pseudovector coupling has one practical advantage, namely, that it permits theoretical physicists to operate with quantities with which they are more familiar. It has, however, a grave disadvantage, namely, that it gives a field theory with which you can calculate only the first order approximation to any process; the second order gives infinite results for any quantity you calculate. This is connected with the fact that the theory cannot be renormalized. The pseudoscalar interaction has the disadvantage that it uses the abstruse operator, γ_5 , which has the strange property that it likes to change a particle of positive energy into a particle of negative energy or, in terms of the hole theory, that the most likely process is the formation of a pair of nucleons. This makes theoretical calculations some-

what more troublesome, but on the other hand, the pseudoscalar theory has the great advantage that it can be renormalized in the sense of field theory and gives finite results for every process in any approximation. So one of the questions is which of these theories is right, and, of course, the theorists hope that the pseudoscalar coupling is right.

The factors G and g in (1) and (2) are simply constants which determine the strength of the coupling. I have written the factor as capital " G " in (1) and as little " g " in (2) because the former is larger than the latter. A very important problem is clearly the determination of the coupling constant G or g ; this plays the same role as the electric charge does in the interaction between charged particles and the electromagnetic field. This latter interaction is governed by the so-called fine-structure constant, $e^2/\hbar c$, which is $1/137$ and, therefore, very small. On the other hand, the corresponding dimensionless quantity of meson theory, $G^2/\hbar c$, is about 15. This, in contrast to $e^2/\hbar c$, is a large number, and this fact is the main cause of trouble in meson theory. All the methods which quantum mechanics has developed in the past were designed for small coupling between field and particle. This assumption of small coupling is very good for the electromagnetic field, and in this case we can predict effects of the order of one part in 10^{-9} , and fit experiment, simply by making an expansion in powers of $e^2/\hbar c$. But it wouldn't be very successful to make an expansion in powers of $G^2/\hbar c$ which is 15; every successive order of approximation would give you a larger result than the previous one.

Now in exploring experimentally the coupling of mesons and nucleons, one turns to the simplest phenomenon which involves this interaction. This is the scattering of mesons by nucleons because it involves only one nucleon and one meson. A slightly more complicated phenomenon is the production of mesons by the interaction of electromagnetic radiation with nucleons, the photoproduction of mesons. In this case you have to consider, in addition to the meson and the nucleon, the interaction with the electromagnetic field. This interaction is known and simple. The next, more complicated, problem is that from which the theory started, namely, the interaction between nucleons which is transmitted by the meson field. This is obviously more complicated because you now have to consider two nucleons and at least one meson. Finally, the most complicated of all phenomena that we hope to deal with is the production of mesons in the collision between two nucleons, in which case we not only have the mesons which produce the force between the two nucleons but, in addition, the meson which is produced in the process.

Scattering of Mesons by Nucleons

The scattering of mesons by nucleons has been investigated experimentally at various places, most extensively at the University of Chicago, with other im-

portant contributions by the teams at Columbia University and the University of Rochester. The results of these investigations seemed at first to be a major defeat for field theory because they seemed to agree with the pseudovector coupling. In making this comparison, the theoretical probability of scattering was calculated by the methods of perturbation theory, i.e., by using only the first term in a power series in $G^2/\hbar c$. In this approximation, pseudoscalar coupling gives a cross section for scattering of mesons by nucleons which is almost independent of energy, while pseudovector coupling yields a cross section which rises very rapidly with increasing energy. The experiments gave a very rapid increase of cross section with energy and thus favored the pseudovector coupling. However, the pseudovector coupling theory in perturbation (weak coupling) approximation predicted also some other things.

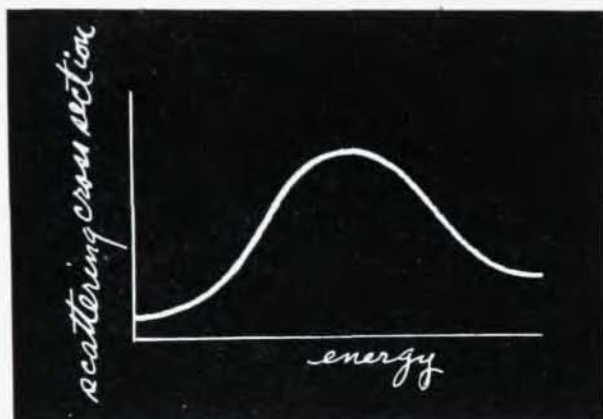
It predicted, for instance, that a negative meson interacting with a proton should in general be simply scattered. In principle, interaction between these two particles could also lead to the reaction $\pi^- + p = n + \pi^0$; but it was predicted by both pseudoscalar and pseudovector theories in the weak coupling approximation that this reaction should not occur with sizeable probability. But, experimentally, it does occur; in fact, the Chicago experiments show that it is about twice as powerful as the simple scattering of the negative mesons. Furthermore, both theories in the weak coupling approximation predict that the positive-meson scattering should be about the same as the negative-meson scattering by protons. This again is wrong: even if you add the charge-exchange scattering to the ordinary scattering of negative mesons, you still get only about a third of the probability of positive-meson scattering. The only possible conclusion from this is that the method of approximation is quite wrong, that one just can't get the right result by calculating merely the lowest power of G that occurs. If $G^2/\hbar c$ is 15, this isn't very surprising. The situation is best illustrated by a song by Arthur Roberts, an experimental physicist of the University of Rochester, who says,

"We have weak coupling and we have strong coupling,
And we have wrong, as we knew all along, coupling."

A more reasonable procedure was proposed by Brueckner of Indiana University and his collaborators, Case and Watson. Taking the strong interaction seriously, they said that nucleon and meson can easily form a sort of compound; i.e., that there exists a virtual quantum state of the system of meson and nucleon. Postulating such a state, they could make use of a lot of calculations which had been made in the period 1940-1945 in an effort to explain the discrepancies between the observed properties of the μ -meson and the theory, and which are known as the strong coupling theory. This theory had predicted that there should be stationary "compound" states of nucleon and meson, and that the first of these should be a state of the following characteristics: the meson has an orbital momentum one, the whole system has a spin of three-

halves so that the state can be described as a $P_{3/2}$ state, and the system is further characterized by a quantity which is called the isotopic spin which also has the magnitude three-halves, $T = 3/2$. I will not explain what that means.

Now, Brueckner proposed that the phenomena of meson scattering are governed by this excited state. The energy of the state is then experimentally determined to be about 300 million volts higher than the ground state of the nucleon. The scattering cross section, both for positive and negative mesons by protons, should then have a resonance maximum near the stationary state and should thus go essentially like this:



The maximum, of course, can be expected to be quite broad because there is a very strong probability that the stationary state will decay into a free meson and a nucleon, and large decay probability is equivalent to a large width of the state.

The main success of Brueckner's theory was that he could predict the ratio of the cross sections for positive-meson scattering and negative-meson scattering. The ratio of the total cross sections should be three to one, which is very close to the observed ratio. Brueckner and his co-workers could further predict that the charge-exchange scattering of negative mesons should be about twice as large as the ordinary scattering of negative mesons and that again agrees with experiment. They could further predict that the angular distribution of the scattered mesons should be about $1 + 3 \cos^2 \theta$ —and this again gives a reasonable approximation to the observed distribution, although it is far from a complete description.

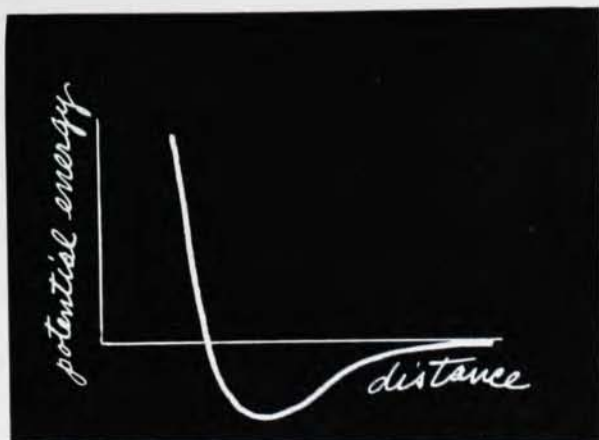
Scattering experiments are generally analyzed in terms of phase shifts of certain partial waves which describe the wave function of the particle. When this is done for meson scattering, it is found that the most important interaction is in the state $P_{3/2}$, $T = 3/2$. In addition to this there is also a strong interaction in the states of orbital momentum zero, that is, in the S states, in spectroscopic notation, and that in this case there is strong interaction both for isotopic spin three-halves and for one-half. For three-halves there is strong re-

pulsion; for one-half there is a somewhat weaker attraction.

Theoretical Developments

Thus the Brueckner theory is quite successful, but, of course, it is purely phenomenological—the existence of an excited state is postulated but nothing is said about its origin. It is desirable to go back to fundamentals in order to explain this state. The road to this was opened by a young French physicist working at The Institute for Advanced Studies, Maurice Lévy, who developed a meson theory of nuclear forces about a year ago. So we are going back to the very beginning of the history of the subject, the theory of nuclear forces which gave the first lead on the pseudoscalar interaction. By consistent use of the pseudoscalar interaction Lévy was able to account for the phenomena observed in nuclear forces. The most important discovery which he made was that, as a direct consequence of pseudoscalar meson theory, the forces between two nucleons are strongly repulsive at small distances. This was the clue that had been missing in previous theories in which the two nucleons had always been considered as perfectly fixed in space. Theory then showed that two such nucleons would always have a strong attraction, indeed so strong that the two nucleons would fall into each other, and not form a stationary state of finite binding energy. Lévy's discovery saved the situation because he showed that there was at small distances a very strong repulsion which prevented the two nucleons from falling into each other.

After Lévy's calculations physicists began to wonder whether the pseudoscalar theory could throw any light on the meson-nucleon scattering experiments. As I said before, the attempt to account for these experiments by weak coupling theory had been a complete failure. The first success with direct application of pseudoscalar theory was achieved by Drell and Henley of Stanford University. They were able to show that between nucleon and meson the same kind of potential exists as between two nucleons according to Lévy, namely one which has a tremendously strong repulsion at small distances. At somewhat larger distances there is an attraction, mainly in the $P_{3/2}$ state. The strong repulsion is independent of angle and, therefore, acts primarily in states of zero angular momentum, that is in S states. Now if you have a strong repulsive potential and calculate the resulting cross section in the first Born approximation, you get a tremendously large result. Since in our case the repulsive potential acts in S states, the scattering is isotropic. It is easy to see that it should also be nearly independent of energy. All these results correspond exactly to the first-order theory which I previously described. The merit of Drell and Henley is that they showed exactly why the first-order result was wrong. Namely, if you have a potential which is strongly repulsive at small distances, and then maybe gets slightly attractive at larger distances, then the only effect of the repulsion on the wave function is to make it essentially zero at the point where the re-



pulsion stops. The most this can do is to give a phase shift proportional to the radius of the repulsive region, and this phase shift will be completely independent of the *magnitude* of the repulsive potential. So Drell and Henley showed not only that the weak coupling theory was wrong all along, but also *why* it was wrong and what should be done instead.

The next major progress was made by Chew, of the University of Illinois, who did the same for the attraction that Drell and Henley had done for the repulsion; namely, he showed how one could calculate, at least in principle, the effects of the attractive force in a sensible way without using perturbation theory. He was able to show that for the $P_{3/2}$, $T = 3/2$ state one should indeed expect a resonance if one only makes suitable assumptions about the magnitude of the coupling constant. Chew used pseudovector coupling for convenience in calculation, but his theory can easily be translated into pseudoscalar coupling.

Building on all this work we, at Cornell University, started last fall to attack the problem from the beginning using the pseudoscalar interaction between nucleon and meson. We were able to explain qualitatively most of the features observed in the scattering experiments. In the first place, we get a strong repulsive interaction in the S state which gives an only moderately large S wave scattering, and this is just what the Chicago and Columbia experiments show. Then the theory gives an attraction in the $P_{3/2}$, $T = 3/2$ state, and the phase shift in this state can be adjusted to fit the experiments by proper choice of the coupling constant. There is just one unknown in the theory, namely, the coupling constant; if you fix the coupling constant to be about 15 you can explain quite well the observed phase shift including its dependence on energy. Finally, you find from the theory that the phase shifts for all the other P states are very small, and this again corresponds to observation. There is only one point which is not yet explained: experimentally, there is an attraction in the S state of isotopic spin $1/2$. But here we know that the theory is still deficient, because although we know that one should renormalize the theory, we are only now learning how to do the renormalization in practice.

Conclusion

I think that one can say at present that although the pseudoscalar meson theory is not yet able to explain quantitatively the meson-nucleon scattering, there is no cause for disbelieving it, because there is no qualitative discrepancy between the predictions of the theory and the experiments. It is likely to be just a matter of learning how to treat strong interactions before we can get quantitative results on meson scattering.

The question of nuclear forces, as I said, is much more complicated. Lévy's first attempt was extremely valuable because it showed that in principle the theory gave the right behavior of nuclear forces. In detail, numerous theoretical physicists have criticized Lévy's paper, and this is not surprising. However, the theory can explain why nuclei hold together, why you have strong forces, and why nucleons do not completely fall into each other. It predicts the interesting phenomenon of many-body forces; that is, it predicts that you have interactions not only between two nucleons, but also between three or more nucleons which hand a meson to each other around the circle. Weisskopf and his collaborators have pointed out that these many-body forces may be quite important for the explanation of the phenomenon of saturation of nuclear forces, that is, for the phenomenon that heavy nuclei also do not collapse. We can deduce from the pseudoscalar theory that nuclear forces depend on spin and deduce that there is a quadrupole moment of the deuteron.

A word must be said about other mesons. The mesons which I have talked about are the π -mesons which have a mass of about 300 electron masses. There are a lot of other mesons of much higher masses. At one time when people calculated only the first-order interaction, some physicists suggested that maybe these heavier mesons would prevent the collapse of nuclei. I think this was false. I think, in fact, that one can see now that these heavier mesons have little to do with the structure of nuclei. This is again connected with Lévy's potential which I mentioned before, which gives a strong repulsion between nucleons at distances of about 0.5×10^{-13} centimeters. Now the heavier mesons could only cause forces of shorter range than this; therefore, no matter what these forces are, they will get swamped by the strong repulsion which exists anyway because of the interaction of the nucleon with the π -meson. Therefore, I think one does not need to know much about heavier mesons in order to construct a satisfactory theory of nuclear forces. Of course, when two nucleons collide at very high speed, they can penetrate the region of mutual repulsion, and then heavy mesons can be produced (as we know experimentally) and probably influence the mechanism of the collision in an important way. But nuclear forces at moderate energies, for instance inside ordinary nuclei, appear to be transmitted mainly by π -mesons which are coupled to nucleons by pseudoscalar interaction. I believe it is only a matter of mathematical skill, but of very great mathematical skill, to extract from the theory the information which we know is buried in it.