Title
POSSIBLE MANIFESTATIONS OF A PION-PION INTERACTION

Author
Chew, Geoffrey F.

Publication Date
1960-01-06

UCRL 9028

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

BERKELEY, CALIFORNIA

DISCLAIMER

UCRL-9028

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

POSSIBLE MANIFESTATIONS OF A PION-PION INTERACTION

Geoffrey F. Chew

January 6, 1960

Printed for the U.S. Atomic Energy Commission

Lawrence Radiation Laboratory
University of California
Berkeley, California

ERRATUM

UCRL-9028, "POSSIBLE MANIFESTATIONS OF A PION-PION INTERACTION," Geoffrey F. Chew, January 6, 1960. Invited paper delivered at the West Coast Meeting of the American Physical Society, December 28, 1959.

In this paper one of the experiments suggested to study a possible P resonance in the $\pi\pi$ system is pion pair production by a photon in the Coulomb field of a nucleus. It has been pointed out to the author by Sidney Drell and by James S. Ball that because two photons are involved, charge-conjugation invariance allows pion production only in states of even orbital angular momentum. Thus the experiment might be relevant to the S-wave $\pi\pi$ interaction, but certainly not to the P-wave. A corresponding argument eliminates 3π states with zero isotopic spin.

In addition Francis E. Low has pointed out that a more detailed calculation is required to show that competition can be overcome from processes in which the momentum is transferred not by the Coulomb field but by nuclear forces. Such a calculation is now being carried out by Yong Duk Kim.

Finally, the author regrets that reference was not made to a paper by C. Goebel, Phys. Rev. Letters 1, 337 (1958), emphasizing the importance of peripheral πN collisions in studying the $\pi\pi$ interaction.

POSSIBLE MANIFESTATIONS OF A PION-PION INTERACTION

Geoffrey F. Chew

Lawrence Radiation Laboratory and Department of Physics
University of California
Berkeley, California

January 6, 1960

ABSTRACT

Various experiments to verify the existence of a P resonance in the $\pi\pi$ system are proposed.

POSSIBLE MANIFESTATIONS OF A PION-PION INTERACTION*

Geoffrey F. Chew

Lawrence Radiation Laboratory and Department of Physics
University of California
Berkeley, California

January 6, 1960

INTRODUCTION

It has been realized for some time that there must be a substantial interaction between every pair of particles in the strongly coupled baryon-meson family. Only the interaction combinations of nucleon-nucleon, hyperon-nucleon, pion-nucleon, and kaon-nucleon have been directly observed, but the failure to see other combinations is presumably only because experimenters find it difficult to make targets of unstable particles. The pion is the lightest particle in the strongly coupled system and in a certain sense the simplest. Therefore the pion-pion interaction, although experimentally elusive, is of great theoretical importance and must be understood before the other and more familiar interactions can be systematically analyzed. The question I want to consider today is how we might get experimental information about the π-π interaction.

A direct pion-pion scattering experiment seems out of the question at present, but there are many indirect approaches possible. One of these has been carried out in considerable detail, even though its relevance to the π-π interaction has only recently been appreciated. This is the study of the electromagnetic structure of the neutron and proton.

NUCLEON ELECTROMAGNETIC STRUCTURE

Nucleons can virtually emit all the various members of the strongly coupled family, and the "cloud" of these particles constitutes what we call the "structure" of the nucleon. The electron-nucleon scattering experiments at Stanford by Hofstadter and collaborators have yielded a number of important characteristics of this cloud and in particular have shown that it has a rather large radius.[1] The cloud must therefore be dominated by virtual pions, since these are the only particles light enough to be allowed by the uncertainty principle to reach large distances from the nucleon center.[2] The magnitude of the nucleon's anomalous magnetic moment allows one to infer the probability for finding pairs of pions in the cloud, a probability which turns out to be very high.

*Invited paper delivered at the West Coast Meeting of the American Physical Society, December 28, 1959.

Now the probability for a nucleon to emit a single pion is well known and is measured by g, the pion-nucleon coupling constant. The probability for emitting an uncorrelated pair of pions one after the other, is therefore known and may be compared with the value required by the nucleon anomalous moment. It turns out to be too small by about a factor of five, as first emphasized by Drell.[3] A mechanism is needed for strongly enhancing the probability of creating pairs of pions in the state with $J = 1$ and $I = 1$, which turn out to be the quantum numbers relevant to electromagnetic structure. A resonance in this state is an obvious possibility and in fact seems to be the only explanation of the situation that does not abandon local-field theory.

Until recently it was not possible to put arguments of this kind into a precise and quantitative form because of the lack of theoretical machinery. Dispersion theory has now filled the gap, and calculations by Frazer and Fulco have established the main characteristics of the resonance required.[4] It should occur at a total energy of the pion pair between three and four pion rest masses in order to give the required nucleon radius and should have a width of ~ 0.4 of the resonance energy in order to give the observed anomalous magnetic moment.

Detailed considerations by Mandelstam and me[5] of the nature of the interaction between two pions have established that this P-wave resonance required by nucleon electromagnetic structure is indeed possible. We also find that S-wave resonances in either $I = 0$ or $I = 2$ states are unlikely. For the sake of today's discussion, therefore, I shall assume that the low energy $\pi - \pi$ system is likely to be dominated by a moderately sharp P-wave resonance. What experiments might be done to confirm or contradict such a theoretical expectation?

ELECTROMAGNETIC PION-PION PRODUCTION

The most direct and satisfactory experiments would produce real pion pairs electromagnetically, free from strong coupling complications. In the near future, various accelerators will give photon beams in the Bev range. Such photons will be capable of producing pion pairs by the same mechanism as for ordinary electron-pair production but of course with a cross section smaller in order of magnitude by $\sim (m_e/m_\pi)^2$. The total energy of these pion pairs in their own rest frame will always tend to be in the general region of the conjectured resonance (that is, equal to a few times the pion rest mass) regardless of the photon energy. What then would govern the choice of photon energy? The answer comes from the requirement that pion-pair production, in order to be clearly interpretable, must take place in the Coulomb field outside the nucleus. The momentum transferred to the nucleus must then be substantially less than the reciprocal of the nuclear radius. A simple calculation shows that this momentum transfer for a photon of energy k producing a pion pair of total energy E (in its own rest frame) is $\sim E^2/2k$. Assuming a resonance energy $\sim 3m_\pi$, we thus require that

$$E^2/2k \approx \frac{9}{2} \frac{m_\pi^2}{k} < R^{-1},$$

or, for $R \sim m_\pi^{-1} A^{1/3}$,

$$k > \frac{9}{2} m_\pi A^{1/3} = 600 \text{ Mev} \times A^{1/3} .$$

Evidently then, one needs several Bev unless the small cross sections of light nuclei can be overcome with a high photon flux.

If the conjectured resonance is present, the cross section for pair production will be enhanced by the same mechanism that gives the large nucleon anomalous magnetic moment. Events in which the nucleus is excited should be ignored. The angles and momenta of the produced pions should be measured and the cross section plotted as a function of the energy of the pion pair (in its own rest frame); the resonance ought to be clearly visible then.

It has been pointed out to me in private conversations by Drell and others at Stanford that an even cleaner experiment is possible if clashing electron-positron beams ever are realized.
The process

$$e^+ + e^- \to \pi^+ + \pi^-$$

is completely free from nuclear complications and produces the pion pair uniquely in the $I = 1$, $J = 1$ state of interest. Furthermore, the order of magnitude of the cross section will be as large as that of any competing process. The electron-positron beam energies envisaged at Stanford would cover very nicely the region of the conjectured resonance, and the total cross section for the reaction would give all the information needed.

A THREE-PION RESONANCE OR BOUND STATE

It might be mentioned at this point that there is theoretical reason to expect that the same attractive forces which produce the conjectured 2π resonance will act so strongly in the 3π state with $I = 0$ and $J = 1$ as to also produce a resonance there and at about the same total energy.[6] The forces might be so strong, in fact, as to give a bound 3π state; if so, this would be the particle proposed by Nambu a number of years ago in order to explain the absence of charge structure in the neutron.[7]

The electromagnetic pion-production experiments discussed above evidently should also reveal the presence or absence of a 3π resonance. If there is a bound state instead of a resonance, the task of detection would be of a different kind. These Nambu particles ought to be produced in almost any nuclear reaction in the Bev range and reveal themselves by the γ decay modes,

$$(3\pi)\ B \begin{cases} \rightarrow \gamma + \pi^0 \\ \rightarrow \gamma + 2\pi^0 \\ \rightarrow \gamma + \pi^+ + \pi^- \end{cases}$$

which would occur with rates $\sim 10^{20}\ \sec^{-1}$. Moyer[8] informs me that identification of γ rays of such anomalously high energy is entirely feasible. Of course, one could also search for evidence in the kinematics of directly observable particles produced at the same time.

PERIPHERAL COLLISIONS

The final type of search for the 2π resonance that I want to discuss today is the one most likely to be tried first. It is based on a proposal made by Low and me a year ago.[9] Here one shoots pions at protons and observes the very-low-energy nucleon recoils. Put in simple language, this experiment attempts to isolate single virtual pions in the cloud of the target proton at a great distance from the center. Collisions of the incident pion with such virtual pions take place just as would free pion-pion collisions--with the nucleon not causing any complications. The whole trick is to pick out those very few collisions that occur far from the center of the nucleon and to ignore the many collisions that are complicated by the inner nucleon structure. This is accomplished by looking only at events with very small momentum transfer to the nucleon.

Consider, for example, the reaction

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n$$

and suppose that the cross section has been measured as a function of the momentum P_n as well as the angle θ_n of the recoil neutron. The total energy E of the $\pi^+ - \pi^-$ pair in its own rest frame is determined by P_n and θ_n, so we may construct the quantity $\dfrac{\delta^2\sigma}{\delta P_n^2\ \delta E^2}$ from our results. Low and I showed that in the limit as P_n^2 approaches $-m_\pi^2$, this quantity approaches a simple limit determined entirely by the pion-nucleon coupling constant and the pion-pion total cross section:

$$\frac{\delta^2\sigma}{\delta E^2\,\delta P_n^2} \to \frac{f^2}{\pi}\;\frac{P_n^2/m_\pi^2}{(P_n^2+m_\pi)^2}\;\frac{E\left(\frac{E^2}{4}-m_\pi^2\right)^{1/2}}{P_L^2}\;\sigma_{\pi^+\pi^-}(E)\,,$$

where P_L is the laboratory momentum of the incident π^-. This limit is of course outside the physical region, but it is not far outside and there is reason to think that the behavior of the cross section for $P_n^2 \sim m_\pi^2$ will strongly reflect the pole and allow at least a rough determination of its residue. In particular, if the anticipated resonance actually exists, it should produce a sharp and characteristic E dependence.

The first experiments at Berkeley of this peripheral-collision type will probably compare the above reaction, controlled by $\sigma_{\pi^+\pi^-}$ and containing the $I = 1$ resonance, with the reaction

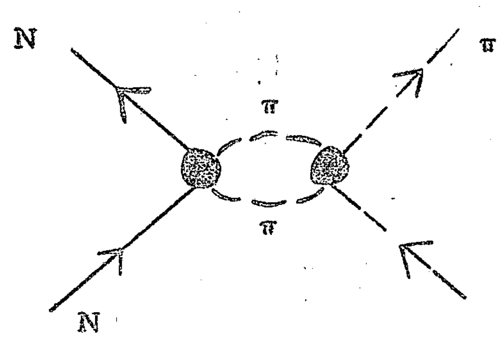
$$\pi^+ + p \to \pi^+ + \pi^+ + n\,,$$

which is controlled by $\sigma_{\pi^+\pi^-}$ and does not contain the conjectured resonance, since the pion pair here is in a pure $I = 2$ state.

OTHER INDIRECT MANIFESTATIONS OF A $\pi\pi$ INTERACTION

The interaction between a pair of pions, if strong, will have indirect consequences of importance to many other interaction combinations. The nucleon-nucleon force, for example, is known to receive a strong contribution from the exchange of pion pairs. If these pairs interact "in transit", the nuclear force obviously will be affected; in particular, there may be a connection between the "hard core" of the nuclear force and the $\pi\pi$ resonance discussed here.

The longest-range part of the pion-nucleon force is determined by the pion-pion interaction, as seen from the following diagram:



That is to say, the lightest system that can be "exchanged" between a pion and a nucleon is a pair of pions. All other exchanged systems will lead to forces of shorter range, and their effects may be suppressed by looking at pion-nucleon collisions with large impact parameter or, equivalently, high angular momentum. Thus one may hope that the information now being developed about pion-nucleon D phase shifts near 300 Mev will bear on the $\pi\pi$ interaction.

Such considerations as these obviously apply to almost any strong interaction. Sooner or later the $\pi\pi$ system must be understood if we are to make substantial further progress in strong-coupling physics.

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

FOOTNOTES

1. For a review of the experiments, see Hofstadter, Bumiller, and Yearian, Revs. Modern Phys. 30, 482 (1958).
2. Roughly speaking, the mean square radius of a particular component of the cloud is given by $\overline{r^2} \approx 6\,E^{-2}$, where E is the total energy of that component. The over-all measured radius corresponds to $\overline{E} \approx 4m_\pi$.
3. S. D. Drell, in 1958 Annual International Conference on High-Energy Physics at CERN (CERN, Geneva, 1958).
4. W. R. Frazer and J. R. Fulco, Effect of a Pion-Pion Scattering Resonance on Nucleon Structure, UCRL-8880, August 1959.
5. G. F. Chew and S. Mandelstam, Theory of the Low-Energy Pion-Pion Interaction, UCRL-8728, April 1959.
6. G. F. Chew, Phys. Rev. Letters 4, to be published (1960).
7. Y. Nambu, Phys. Rev. 106, 1366 (L) (1957).
8. Professor Burton Moyer, Lawrence Radiation Laboratory, private communication.
9. G. F. Chew and F. Low, Phys. Rev. 113, 1640 (1959).