THREE-PION RESONANCE OR BOUND STATE*

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It has been shown by Frazer and Fulco[1] that a two-pion P-wave resonance at a total energy between three and four pion rest masses can account for the isotopic vector component of nucleon electromagnetic structure. The mean square radius both of the isovector charge and the anomalous magnetic moment is essentially determined by the energy of this resonance ($\langle r^2\rangle_{av} \approx 6E_R^{-2}$). It continues to be a mystery, however, why the isotopic scalar charge experimentally should have nearly this same radius again, since the isoscalar electromagnetic structure is presumably dominated by a three-pion configuration.[2,3] The purpose of this note is to point out that it is not unreasonable to expect a three-pion resonance or even a bound state at roughly the same energy as the two-pion resonance. According to an argument given earlier by the author in terms of unsubtracted dispersion relations,[4] such a circumstance might explain the experimental absence of neutron charge structure.

The essential point is that in the particular three-pion state involved in nucleon electromagnetic structure, each pair of pions feels the same strong attractive force as that producing the two-pion resonance. The three-pion state has $I=0$, $J=1$, and odd parity.[2,3] It is easy to verify that the isotopic spin function is antisymmetric under exchange of any pair, and therefore each pair is in a pure $I=1$ state. The relative angular momentum of any pair can be 1, 3, 5..., etc., but the proportion of $l=1$ at low energies must be very large.[5] Thus the strong attractive force between P-wave pions occurs in all three pairs of the three-pion state of interest, and it seems not unlikely that the extra potential energy could compensate for the rest mass of the third pion and produce a resonance at about the same total energy as that of the two-pion system.

In fact the attraction might easily be so great as to produce a bound state, that is, a particle of mass slightly less than $3m_\pi$, with $I=0$, $J=1$, and odd parity. Such a vector meson has been discussed by Nambu,[6] who proposed it as a new elementary particle. However, the effect on nucleon electromagnetic structure would be the same for the three-pion bound state, and so would the other experimental manifestations of the vector meson discussed by Nambu.

The question naturally arises as to whether further resonances or bound states could result from configurations of still higher pion number. First of all, such configurations would not be stable unless they had energies less than $2m_\pi$ if the G parity is even or $3m_\pi$ if the G parity is odd. Furthermore, it is unlikely that the rest energy of additional pions can continue to be compensated by potential energy of attraction because the strong attractive force occurs in only one particular pair configuration. This configuration happens to occur almost with 100% probability for all pairs of our particular three-pion state, but such a circumstance probably cannot be repeated with higher pion numbers.

It is to be hoped that when the detailed nature of the force between two pions has been understood, one can make at least a crude calculation of the three-pion system. A relativistic three-body problem, however, is sure to be very difficult, and confirmation of the resonance or bound state must come from other sources. Should the state actually be bound, then the decay products discussed by Nambu[6] may be sought.[7] A resonance will be more difficult to establish but will have the same virtual manifestations as a bound state. For example, there will be a strong short-range contribution to the nuclear force which may, as Nambu suggested, have something to do with the hard core. Similar short-range interactions due to the exchange of the three-pion state will occur in many other situations. Really convincing evidence could come from some reaction in which three pions are produced electromagnetically, say by a high-energy photon in a Coulomb field or by the clashing positron-electron beams envisaged at Stanford. Here a resonance could be unmistakably established.

The author is grateful to Dr. Robert Karplus, Dr. Stanley Mandelstam, and Dr. Ben Mottelson for discussion of these ideas, which are about one year old. They have not been published previously, partly because the author's preoccupa-

tion with another problem prevented a careful investigation and partly because experimental consequences seemed remote. Recently, however, Dr. Burton J. Moyer in a private conversation informed the author that an experimental search for the Nambu particle is quite feasible. If these superficial remarks serve to encourage such a search, they are perhaps justified.

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[1]W. R. Frazer and J. R. Fulco, Phys. Rev. Letters 2, 365 (1959).

[2]Geoffrey F. Chew, Robert Karplus, Stephen Gasiorowicz, and Fredrik Zachariasen, Phys. Rev. 110, 265 (1958).

[3]P. Federbush, M. L. Goldberger, and S. B. Treiman, Phys. Rev. 112, 642 (1958).

[4]Geoffrey F. Chew, University of California Radiation Laboratory Report UCRL-8194, February, 1958 (unpublished).

[5]It was pointed out to the author by Ben Mottelson that a three-pion state with $J=1$ and odd parity can be constructed which has only $l=1$ relative angular momentum for each pair.

[6]Yoichiro Nambu, Phys. Rev. 106, 1366 (1957).

[7]Presumably, the most important decay modes are $(3\pi)_B \to \pi^0+\gamma$ and $(3\pi)_B \to \pi^+ + \pi^- + \gamma$, with rates $\sim 10^{20}$ $\sec^{-1}$.

EFFECTS OF TWO ADDITIONAL PARTICLES ON THE SYMMETRIES IN STRONG INTERACTIONS*

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It is well known that, within the framework of the formula of Gell-Mann[1] and Nishijima[2] relating the strangeness of a particle to its baryon number, charge, and third component of its isotopic spin, there is room for additional particles. One of these, which we shall call D, following Yamanouchi,[3] is a positively charged meson with strangeness $S=2$ and isotopic spin $I=0$. Another, which we shall call Ω,[4] is a negatively charged baryon with $S=-3$ and $I=0$.[5] It is the purpose of this note to point out that if the D and Ω exist, the conclusions of a number of authors[6-9] about the symmetries of the strong interactions must be modified.

If we consider only meson-baryon interactions which are linear in the meson fields and bilinear in the baryon fields, the most general charge-independent interactions including the new particles are of the form

$$H_\pi = G_{\pi NN}\bar{N}\vec{\tau}\cdot\vec{\pi}N + G_{\pi\Lambda\Sigma}(\bar{\Lambda}\vec{\pi}\cdot\vec{\Sigma}+\text{H.c.}) + G_{\pi\Sigma\Sigma}\vec{\bar{\Sigma}}\cdot\vec{\pi}\times\vec{\Sigma} + G_{\pi\Xi\Xi}\bar{\Xi}\vec{\tau}\cdot\vec{\pi}\Xi,$$

$$H_K = G_{K\Lambda N}(\bar{N}K\Lambda+\text{H.c.}) + G_{K\Sigma N}(\bar{N}K\vec{\tau}\cdot\vec{\Sigma}+\text{H.c.}) + G_{K\Lambda\Xi}(\bar{\Xi}K_c\Lambda+\text{H.c.}) + G_{K\Sigma\Xi}(\bar{\Xi}K_c\vec{\tau}\cdot\vec{\Sigma}+\text{H.c.}) + G_{K\Xi\Omega}(\bar{\Xi}K\Omega+\text{H.c.}),$$

$$H_D = G_{DN\Xi}(\bar{N}D\Xi+\text{H.c.}) + G_{D\Lambda\Omega}(\bar{\Lambda}D\Omega+\text{H.c.}), \qquad (1)$$

where H.c. stands for Hermitian conjugate and we use the notation of Gell-Mann[7] that the symbol for a particle stands for the operator that annihilates it. Here K is a spinor and K_C the charge conjugate spinor, and they are given by

$$K=\begin{pmatrix}K^+\\K^0\end{pmatrix},\quad K_C=\begin{pmatrix}\bar{K}^0\\-K^-\end{pmatrix}.$$

In (1) we have emphasized the form of the interaction in isotopic spin space. If the π, K, and D are all pseudoscalar mesons, and all the baryons have the same spin and parity, then all the interactions in (1) will contain an additional factor which will be either γ_5 (pseudoscalar coupling) or $\gamma_5\gamma_\mu\partial/\partial x_\mu$ (pseudovector coupling).

In the absence of further symmetries, there are eleven coupling constants to be determined before the interactions are specified. However, we can postulate that all pion-baryon coupling constants are equal (global symmetry), all K-baryon couplings are equal (cosmic symmetry), and all D-baryon couplings are equal (which we might as well call galactic symmetry). Then the number of independent coupling constants is reduced to three: G_π, G_K, and G_D. (If the interactions are pseudovector, we can speculate that there is only one dimensionless coupling constant, i.e., $M_\pi G_\pi = M_K G_K = M_D G_D$, where the M's are the meson masses. The constants $M_\pi G_\pi$ and $M_K G_K$ appear to be approximately equal experimentally.)

One of the reasons for postulating the existence