IV. APPLICATION

The low-energy limit derived in the previous section is the result of the theory of composite particles and of gauge invariance. It is interesting, therefore, to apply this result to the n-p capture ($M1$ transition) in order to compare the theory with experiment.

As we have shown,[1] the effect of rescattering in the n-p state can be obtained as a function of the n-p phase shift by using unitarity. The low-energy limit obtained in the previous section and the enhancement factor due to the rescattering effect will give a good approximation for the $M1$ amplitude and allows comparison with experiment. This subject has been discussed in detail in reference 1.

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G Parity and the Interactions of Heavy Mesons*

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Some implications of the G parity of heavy mesons are discussed. It is pointed out that the G parity of a meson may determine whether it can contribute to a pole term in the nucleon-nucleon scattering amplitude. Since G parity may not be conserved in the decays of some heavy mesons, G must be determined indirectly. One method is to measure the charge parity of the decay products of a neutral meson, a quantity which determines G is the isospin of the meson is known. Selection rules for the decay of neutral and charged mesons are given. Results are applied to the ζ and η mesons.

RECENTLY a number of heavy mesons of strangeness zero have been discovered, the ω, ρ, η, and ζ,[1] and there may be more to come. Four quantum numbers are required to specify such mesons (in addition to the strangeness which is zero): the spin J, parity P, isospin T, and G parity. We wish to point out some consequences of the G parity for the interactions of these mesons with nucleons, and to emphasize that it may not always be trivial to measure G. We illustrate the problem by considering the ζ and η mesons and mention some (admittedly difficult) experiments which can distinguish between the alternative possibilities.

The G parity of n pions is $G=(-1)^n$. Thus, if a meson decays into pions with conservation of G, its G parity is determined simply by counting the number of final-state pions. However, as has been discussed by Feld[2] and others, G may not be conserved in the decay of these mesons because of coupling to the electromagnetic field. Despite this fact, if the interaction which causes the decay is invariant under charge conjugation C, then the properties of the decay products under C can be used to obtain the G parity of the meson. In the following, we consider only decays with lifetimes which are very short compared to typical weak interaction lifetimes and assume that P and C are conserved.

Before discussing the measurement of G, we shall point out how the meson G parity affects its interactions with nucleons. If the interaction is linear in the meson field, the meson should have the same quantum numbers as a bound state of a nucleon-antinucleon pair. The parity and G parity of such a pair are[3]

$$P=-(-1)^L,\quad G=(-1)^{S+T+L}, \tag{1}$$

where S, T, and L are the spin, isospin, and orbital angular momentum of the pair. For neutral mesons (including the neutral members of multiplets), G and C are related by

$$G=C(-1)^T. \tag{2}$$

From (1) and (2), we obtain for neutral mesons which interact linearly with nucleons the following relations

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TABLE I. Selection rules for the decay of neutral heavy mesons. The quantum numbers J (spin), P (parity), T (isospin), and G parity apply to all members of a meson multiplet, but the C parity applies only to the neutral member. An allowed decay mode is indicated by "yes," and forbidden decays are indicated by the symbol for the conservation law which would be violated by the decay. A decay in which a photon appears is indicated as violating G if otherwise allowed.

Quantum numbers of meson			Decay modes												
T	J^{PG}	C	$N\bar{N}$	$\pi^+\pi^-$	$\pi^0\pi^0$	$\gamma\gamma$	$\pi^0\gamma$	$\pi^+\pi^-\pi^0$	$\pi^0\gamma\gamma$	$\pi^0\pi^0\pi^0$	$\pi^0\pi^0\gamma$	$\pi^+\pi^-\gamma$	$4\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^+\pi^-\pi^-$
0	0^{++}	+	yes	yes	yes	G	J	P	G	P	C	G	yes	yes	yes
0	0^{+-}	−	C	C	C	C	J	P	C	P	G	G	C	G	G
1	0^{++}	−	C	C	C	C	J	P	C	P	G	G	C	yes	yes
1	0^{+-}	+	yes	G	G	G	J	P	G	P	C	G	G	G	G
0	0^{-+}	+	yes	P	P	G	J	G	G	G	C	G	yes	yes	yes
0	0^{--}	−	C	P	P	C	J	yes	C	C	G	G	C	G	G
1	0^{-+}	−	C	P	P	C	J	G	C	C	G	G	C	yes	yes
1	0^{--}	+	yes	P	P	G	J	yes	G	yes	C	G	G	G	G
0	1^{-+}	+	C	C	J	J	C	G	G	G	C	G	yes	yes	yes
0	1^{--}	−	yes	G	J	J	G	yes	C	C	G	G	C	G	G
1	1^{-+}	−	yes	yes	J	J	G	G	C	C	G	G	C	yes	yes
1	1^{--}	+	C	C	J	J	C	yes	G	yes	C	G	G	G	G
0	1^{++}	+	yes	P	J	J	C	G	G	G	C	G	yes	yes	yes
0	1^{+-}	−	yes	P	J	J	G	yes	C	C	G	G	C	G	G
1	1^{++}	−	yes	P	J	J	G	G	C	C	G	G	C	yes	yes
1	1^{+-}	+	yes	P	J	J	C	yes	G	yes	C	G	G	G	G

between J, P, and C:

$$\begin{aligned} &J=0, \quad P=\pm \qquad \text{implies } C=+, \\ &J\geq 1, \quad P=(-1)^J \quad \text{implies } C=-, \\ &J\geq 1, \quad P=(-1)^{J+1} \text{ implies } C=\pm. \end{aligned} \tag{3}$$

But a neutral scalar meson coupled to nucleons by a vector interaction has $C=-$,[4] in contradiction to (3). This means that although the interaction is apparently linear in the meson field, it has a zero matrix element between a meson state and a nucleon-antinucleon state. Such an apparently linear interaction is equivalent to an interaction which is bilinear in the meson field.

In the language of dispersion relations, for a meson to give rise to a pole term in the nucleon-nucleon and nucleon-antinucleon scattering amplitudes, the meson must have $T\leq 1$, $G=C(-1)^T$, and C must be given by (3).

Considering only cases with $T\leq 1$, $J\leq 1$, but with either value of P and G, there are 16 possible mesons, only 10 of which can give rise to pole terms. Even if a meson has the "wrong" G to give rise to a pole, it does not have to be produced in pairs, since additional particles (e.g., pions) can insure G conservation.

Now consider decay interactions. Whether or not G is conserved it is possible to deduce G from the C parity of the decay products. Since charged mesons are not eigenstates of C, it is useful to consider decays of neutral mesons. In Table I we give selection rules for the decays of neutral mesons with various values of T, J, P, and G. We also list whether the meson has the same quantum numbers as a possible state of a nucleon-antinucleon pair. In Table II are listed selection rules for the decay of positively charged mesons. Some of these selection rules have appeared previously in the literature.

To illustrate the difficulties in measuring C, consider the ζ and η mesons. Sechi Zorn[5] has shown that the ζ has $T=1$ from its production in the reaction

$$p+p\rightarrow d+\zeta^+. \tag{4}$$

Since the ζ^+ decays into two pions, conservation of T and G implies the assignment $1^{-+}(J=1, P=-, G=+)$. However, the ζ appears to have a narrow width,[5] a fact that suggests that T and G may not be conserved. Excluding $J\geq 2$, the remaining assignments are 1^{--}, 0^{++}, and 0^{+-}. This last is just the particle predicted by Lichtenberg, Kovacs, and McManus[6] from an analysis of nucleon-nucleon scattering. A measurement of the width of the ζ is clearly important.

TABLE II. Selection rules for the decay of positively charged $T=1$ mesons. For further explanation see the caption for Table I.

Quantum numbers of meson	Decay modes					
J^{PG}	$N\bar{N}$	$\pi^+\pi^0$	$\pi^+\gamma$	$\pi^+\pi^0\pi^0$ $\pi^+\pi^+\pi^-$	$\pi^+\pi^0\gamma$ $\pi^+\gamma\gamma$	$\pi^+\pi^0\pi^0\pi^0$ $\pi^+\pi^+\pi^-\pi^0$
0^{++}	G	T	J	P	G	yes
0^{+-}	yes	T, G	J	P	G	G
0^{-+}	G	P	J	G	G	yes
0^{--}	yes	P	J	yes	G	G
1^{-+}	yes	yes	G	G	G	yes
1^{--}	G	G	G	yes	G	G
1^{++}	yes	P	G	G	G	yes
1^{+-}	yes	P	G	yes	G	G

[4] See, e.g., E. Corinaldesi, Nuclear Phys. 7, 305 (1958). See pp. 343–344.

[5] B. Sechi Zorn, Phys. Rev. Letters 8, 282 (1962).

[6] D. Lichtenberg, J. Kovacs, and H. McManus, Bull. Am. Phys. Soc. 7, 55 (1962). The abstract to this reference erroneously states that decay into four pions is allowed. Five pions is the smallest number allowed, and this is forbidden energetically.

Since G may be violated in the decay of the charged ζ, we consider the C parity of the decay products of the ζ^0. The charged mode $\zeta^0 \to \pi^+ + \pi^-$ has not been observed. If it is seen, this would rule out the assignments 1^{--} and 0^{++}. However, observation of this mode does not distinguish between 1^{-+} and 0^{+-}. Therefore, if the mode $\zeta^0 \to \pi^+ + \pi^-$ is seen, it is useful to look for either the decays

$$\zeta^0 \to 2\pi^0, \quad \zeta^0 \to 2\gamma \tag{5}$$

for which $C = +$, $G = -$, or the decay

$$\zeta^0 \to \pi^0 + \gamma \tag{6}$$

for which $C = -$, $G = +$. If the mode $\zeta^0 \to \pi^+ + \pi^-$ is not seen, it may indicate that the ζ has either the quantum numbers 1^{--} or 0^{++}, as this is forbidden for these assignments. In the former case the decay $\zeta^0 \to \pi^0 + 2\gamma$ is allowed, while in the latter case the decay $\zeta^0 \to 2\pi^0 + \gamma$ should occur.[7]

Another possibility to distinguish between 1^{-+} and 0^{+-} is to obtain a qualitative measurement of the ratio

$$R = (\zeta^0 \to \text{neutrals})/(\zeta^0 \to \pi^+ + \pi^-).$$

If the ζ has 1^{-+}, the dominant *neutral* mode is (6), which has an available phase space comparable to that for the mode $\zeta^0 \to \pi^+ + \pi^-$. But the transition probability for (6) will contain an extra factor of $\alpha = 1/137$, so that $R \approx 0.01$. However, if the ζ has 0^{+-}, the mode $\zeta^0 \to \pi^+ + \pi^-$ also proceeds indirectly via the electromagnetic interaction, and R is probably greater than 1.

Aside from the experimental problem of measuring (5) or (6), there is the difficulty of distinguishing the ζ^0 from the η, assuming the η has $T=0$,[8] unless they can be separated by their masses in a high-resolution experiment. We can think of no experimentally feasible reaction in which the production of ζ^0 is allowed and production of η forbidden on the basis of isospin conservation alone. The difficulty is that there is no known particle with $T=1$, $T_2=0$ sufficiently stable to form a beam. On the other hand, the η can be produced without the ζ^0 in a reaction with only $T=0$ particles, e.g.,

$$d + d \to d + d + \eta, \quad d + d \to \mathrm{He}^4 + \eta,$$

in analogy with the interaction $d + d \to \mathrm{He}^4 + \omega$ suggested by Feinberg.[9]

The C parity of the η can also be measured by looking at the neutral decay modes to determine whether the number of photons is even or odd. The η was observed[10] in $K^- p$ interactions leading to the final states

$$\begin{aligned} K^- + p &\to \Lambda + \pi^+ + \pi^- + \pi^0 \\ &\to \Lambda + \text{neutrals}. \end{aligned}$$

Again, one must be certain that the neutral decays are in fact the decays of the η rather than of the ζ^0 (see, however, reference 8). Observation of events of the type

$$K^- + p \to \Lambda + \pi^+ + \pi^-$$

would provide additional information. More generally, a measurement of the ratios

$$(\pi^+ + \pi^-)/(\pi^+ + \pi^- + \pi^0)/(\text{neutrals})/(\pi^+ + \pi^- + \gamma)$$

produced in different reactions at the appropriate internal energy (~ 570 MeV) would be helpful.

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[7] The possibility that two-pion decay of the ζ^0 may be forbidden has been noted independently by G. Feinberg and A. Pais, Phys. Rev. Letters **8**, 341 (1962), and by M. Ross (private communication).

[8] M. Ross, Phys. Rev. Letters **8**, 417 (1962), has suggested that the η is the neutral member of the ζ triplet. Assuming $J < 2$, this implies the assignment 1^{--}, provided the decay of the ζ^+ is really $\zeta^+ \to \pi^+ + \pi^0$.

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