Heavy Mesons and the Charge Independence of the Nuclear Forces.

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According to a recent experiment (1) the mass spectrum of the neutral component of ρ-meson appears to be resolved into two levels, one of which is almost degenerate with the ω meson within experimental errors. This has raised some interesting possibilities. Fubini (2) has proposed a drastic suggestion: There may exist a vector meson, called Γ, which has no well defined isospin and decays into both of $T=0$ and $T=1$ states, violating the charge independence (C.I.). The ρ_0 and ω peaks are the manifestations of different decay modes of the same particle. On the other hand, a conventional way of dealing with this degeneracy has been given by Glashow (3,4). According to Glashow ρ_0 and ω are different particles, but, because of the small mass difference, the electromagnetic transition between them can be quite appreciable and the observed particles are mixtures of ρ_0 and ω. The extent to which ρ_0 and ω are mixed has been estimated (4,5). The theoretical results for the C.I. violating decay $\omega\to 2\pi$ are reasonable, showing that Glashow's explanation is not unnatural. It may seem, therefore, that it is not necessary to introduce Fubini's drastic hypothesis. This does not, however, necessarily mean that Fubini's hypothesis is eliminated. Rather it seems difficult to tell, by observing the decays, which of the two is realized in nature. In this note we wish to examine the possibility of finding the differences between these two theories in their effects on nuclear forces.

For simplicity, first we assume that Fubini's Γ interacts with the nucleon by a factor $(1+\tau_3)/2$ (maximum violation of C.I.), then the Γ-exchange takes place only in p-p, but not in p-n nor in n-n systems. The static potential for p-p system arising from single Γ-exchange is

$$V(r)=f^2\exp[-\mu_1 r]/r\,, \tag{1}$$

where f is the Γ-$\mathcal{N}$ coupling constant and $\mu=m_\Gamma c/\hbar$.

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(1) J. Button, G. R. Kalbfleisch, G. R. Lynch, B. C. Maglić, A. H. Rosenfeld and M. L. Stevenson: UCRL-9814 (1961).

(2) S. Fubini: *Phys. Rev. Lett.*, **7**, 466 (1961).

(3) S. L. Glashow: *Phys. Rev. Lett.*, **7**, 469 (1961).

(4) Y. Nambu and J. J. Sakurai: *Phys. Rev. Lett.*, **8**, 79 (1962).

(5) G. Feinberg: *Phys. Rev. Lett.*, **8**, 151 (1962); B. T. Feld: *Phys. Rev. Lett.*, **8**, 181 (1962).

Turning to Glashow's theory, we denote ω and ρ_0-fields by φ_s and φ_v respectively. The mass or life-time eigenstates are given by superpositions of φ_s and φ_v

$$\text{(2)} \qquad \psi_1 = \alpha\varphi_s + \beta\varphi_v\,, \qquad \psi_2 = \beta\varphi_s - \alpha\varphi_v\,,$$

with $\alpha^2+\beta^2=1$. Accordingly the interaction with the nucleon can be written as

$$\text{(3)} \qquad \mathcal{N}[f_s\varphi_s + f_v\tau_3\varphi_v]\mathcal{N} \to \mathcal{N}[(\alpha f_s + \beta f_v\tau_3)\psi_1 + (\beta f_s - \alpha f_v\tau_3)\psi_2]\mathcal{N}\,,$$

where f_s and f_v are coupling constants. The potentials arising froms ingle exchange of ψ_1 or ψ_2 are respectively given by

$$\text{(4)} \qquad \begin{cases} (\alpha f_s + \beta f_v\tau_3^{(1)})(\alpha f_s + \beta f_v\tau_3^{(2)}) \exp[-\mu_1 r]/r\,, \\[2ex] (\beta f_s - \alpha f_v\tau_3^{(1)})(\beta f_s - \alpha f_v\tau_3^{(2)}) \exp[-\mu_2 r]/r\,. \end{cases}$$

Each field violates the C.I. just as Γ does. But if we put $\mu_1=\mu_2=\mu$ the sum of these two potentials becomes

$$\text{(5)} \qquad f_s^2 + f_v^2\tau_3^{(1)}\tau_3^{(2)}] \exp[-\mu r]/r\,,$$

and the C.I. is restored. Actually the mass-splitting μ_1-μ_2 will be very small, so the C.I. violation due to ψ_1 and ψ_2 will be quite negligible. It is important to note that in Glashow's theory we have a doublet while Fubini's Γ can exist singly.

We wish to discuss the possibility of detecting the effects of Γ-meson on the nuclear forces. As noted by Fubini, the effect of the Γ-exchange potential is expected to be small at low energies because its force range is very short. However, the scattering lengths for ^1S states of p-p, n-n and p-n systems, a_{pp}, a_{nn} and a_{pn}, are extremely sensitive to the variations in the potentials. So it will be interesting to estimate the effect on these quantities.

The Γ-exchange potential $V(r)$ (1) is repulsive and makes the p-p potential shallower than the n-n and the p-n ones. We have estimated the variation of a_{pp} due to $V(r)$ by Schwinger's method ([6,7]), using the same assumptions regarding the potential as those of SALPETER ([7]), *i.e.* a central potential for the p-p singlet state consisting of an infinite rectangular repulsive potential of core radius r_c plus an attractive potential outside the core of the Hulthén shape.

The mass of the Γ-meson has been taken as 770 MeV. The results, $f^{-2}b_0\delta(a_{pp}^{-1})$, for $r_c=0,\ 0.3,\ 0.6\cdot10^{-13}$ cm are given in Table I. A reasonable value of r_c will be between 0.3 and $0.6\cdot10^{-13}$ cm ([8]). If the Γ-$\mathcal{N}$ vertex has the factor $(1+\lambda\tau_3)$ instead of $(1+\tau_3)$, the contributions of Γ-exchange to V_{pp}, V_{nn} and V_{pn} are given by (1) multiplied by $(1+\lambda)^2/4$, $(1-\lambda)^2/4$ and $(1-\lambda^2)/4$, respectively. Being proportional to the strengths of the variations in the potentials, $\delta(a_{pp}^{-1})$, $\delta(a_{nn}^{-1})$ and $\delta(a_{pn}^{-1})$ with $\lambda\neq1$ are easily obtained from the value of $\delta(a_{pp}^{-1})$ with $\lambda=1$. The assumption of too small a value of λ will make Fubini's hypothesis less interesting.

([6]) J. SCHWINGER: *Phys. Rev.*, **78**, 135 (1950).

([7]) E. E. SALPETER: *Phys. Rev.*, **91**, 994 (1953).

([8]) See *e.g.* J. L. GAMMEL and R. M. THALER: *Progr. in Elem. Particle and Cosmic Ray Phys.*, **5**, 99 (1960).

Evidence for two other mesons ζ and η, with masses around 560 MeV, has been obtained in recent experiments. Spin-parity 1^- has been suggested for both the mesons. On the experimental side ζ appears to have 1^- while some evidence ([9]) has been reported for spin-parity 0^- for the η meson. If we assume the 1^- assignment for both of the mesons, a situation similar to the ρ_0, ω pair is also seen to exist here. We have considered this possibility also. The corresponding meson will be denoted by Γ' and other corresponding quantities also with a prime. The results are shown in Table I.

TABLE I. – $b_0=\hbar^2/Me^2=28.81$ fermi. M is the nucleon mass.

r_c (in fermi)	0	0.3	0.6
a_{pp} (in fermi)	18.1	16.5	15.7
$b_0(a_{pp}^{-1}-a_{pn}^{-1})$	0.37	0.53	0.61
$f^{-2}b_0\,\delta(a_{pp}^{-1})_\Gamma$	8.47	2.22	0.85
$f'^{-2}b_0\,\delta(a_{pp}^{-1})_{\Gamma'}$	13.90	5.34	2.75

The value of the scattering length a_{pp} in the p-p system as derived from the data (after elimination of the Coulomb effects) is dependent on the assumed shape of the wave function of the potential. SALPETER ([7]) has made an analysis assuming that the potential consists of a hard core plus an attractive Hulthén potential. His results are quoted in Table I.

For a_{nn}, ILAKOVAC *et al.* ([10]) have recently made an analysis of the proton spectrum from d(n, p)2n taking into account only the n-n interaction in the final state, and have obtained a value $a_{nn}=(22\pm2)$ fermi ([*]). The error given is entirely statistical and does not contain estimates of the accuracy of the theory. They noted that the shape of the proton spectrum is definitely sensitive to the value of a_{nn} and is very useful fori ts accurate determination. On the other hand, a_{pn} is precisely known as $a_{pn}=(23.69\pm0.06)$ fermi ([11]). There is a slight but definite difference between b_0/a_{pp} and $b_0/a_{pn}=1.216\pm0.003$, as shown in Table I.

Now let us discuss the Γ-effect on the differences among a_{pp}, a_{nn} and a_{pn}.

i) $a_{pp}-a_{nn}$. Let us have an idea of the order of magnitude of the Γ-effect. If $r_c=0.3$ fermi, we have $\delta(a_{pp}^{-1})_\Gamma=2.22f^2/b_0$ fermi^{-1}, or substituting $a_{pp}=16.5$ fermi, we have $\delta a_{pp}=-21.0f^2$ fermi. If the coupling strength is $f^2\gtrsim1$ as suggested by Sakurai's ([12]) estimation on the basis of the nucleon structure, the Γ-effect is quite large. Besides the Γ-effect, the magnetic interaction also destroys the charge symmetry, giving a small contribution to $a_{pp}-a_{nn}$ in the same direction with the

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([9]) P. L. BASTIEN, J. P. BERGE, O. I. DAHL, M. FERRO-LUZZI, D. H. MILLER, J. J. MURRAY, A. H. ROSENFELD and M. B. WATSON: *Phys. Rev. Lett.*, **8**, 114 (1962); **8**, 302 (1962); L. M. BROWN and P. SINGER: *Phys. Rev. Lett.*, **8**, 155 (1962); E. PICKUP, D. K. ROBINSON and E. G. SALANT: *Phys. Rev. Lett.*, **8**, 329 (1962).

([10]) K. ILAKOVAC, L. G. KUO, M. PETRAVIĆ and I. ŠLAUS: *Proc. Rutherford Jubilee Internat. Conf.* (editor: J. B. BIRKS) (London, 1961), p. 157.

([*]) We take the signs of a's as positive.

([11]) See *e.g.* L. HULTHÉN and M. SUGAWARA: *Handb. d. Phys.*, **34**, 1 (1957).

([12]) J. J. SAKURAI: *Phys. Rev. Lett.*, **7**, 355 (1961).

Γ-effect [6,7,13]. If the Γ-meson exists, we shall have $a_{nn} \gg a_{pp}$. The result of ILAKOVAC *et al.*, though it is not very accurate, is unfavorable to the existence of the Γ-meson.

ii) $a_{pp} - a_{pn}$. If $f^2 \geqslant 1$, the C.I. violating effect of Γ well exceeds the observed difference $b_0(a_{pp}^{-1} - a_{pn}^{-1})$. Besides this Γ-effect and the magnetic interaction, the effect of $\pi^{\pm}, \pi^0$ mass difference destroys the C.I. These three give contributions with the same sign to $a_{pp} - a_{pn}$ [6,7,13]. Especially the pion mass difference effect (examined up to two pion exchange potential) seems big enough to explain the gap between V_{pp} and V_{pn}. If we accept this, then very little room will be left for the Γ-effect and therefore the Γ-effect estimated above will be too big.

Finally we would like to note the effect of the heavy mesons on the $\boldsymbol{L}\cdot\boldsymbol{S}$ force. Following SAKURAI [14], it is very attractive to consider that vector mesons would provide an unified explanation for an $\boldsymbol{L}\cdot\boldsymbol{S}$ force of the required sign and magnitude, a repulsive core in the $\mathcal{N}$-$\mathcal{N}$ system and a strong attraction in the $\mathcal{N}$-$\overline{\mathcal{N}}$ system. These three are all difficult problems to explain in terms of the pion theory. If a large portion of the $\boldsymbol{L}\cdot\boldsymbol{S}$ force comes from the Γ-mesons, violation of the C.I. will be observed, for example, in polarization phenomena. TINLOT and WARNER [15] have measured the polarization in the quasi-elastic p-n scattering and compared it with the theoretical prediction of BREIT *et al.* [16]. But at present it seems to be premature to infer about the charge being independent of this data.

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(14) J. J. SAKURAI: *Ann. Phys.*, **11**, 1 (1960); *Phys. Rev.*, **119**, 1786 (1960); G. BREIT: *Phys. Rev.*, **120**, 287 (1960).

(15) J. H. TINLOT and R. E. WARNER: *Phys. Rev.*, **124**, 890 (1961); **125**, 1028 (1962).

(16) M. H. HULL, Jr., K. E. LASSILA, H. M. RUPPEL, R. A. MCDONALD and G. BREIT: *Phys. Rev.*, **122**, 1606 (1961).