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THEORY OF SPIN-ORBIT INTERACTION IN NUCLEAR FORCES*

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It has repeatedly been pointed out in recent years[1-4] that a spin-orbit interaction between two nucleons is necessary to explain the observed scattering of nucleons. From a theoretical point of view the existence of a spin-orbit interaction is not at all surprising, because it has been shown by Breit[5] that in a relativistic treatment of the interaction of nucleons the spin-orbit interaction arises in a natural way. However, pion-theoretical calculations by Klein[6] and several other authors[7] show that the pion theory is unable to account for the large spin-orbit interaction, which is required to explain the experimental results. It is, therefore, necessary to look for some other explanation of the spin-orbit interaction.

Recently we have predicted[8,9] the existence of a hitherto unobserved neutral scalar meson, the ρ^0 meson, which is coupled strongly to the nucleons. Since the mass of the ρ^0 meson is considerably larger than the pion mass, it leads to a force of very short range between the nucleons. The second-order nuclear potential due to the ρ^0 meson is given by

$$V_2(\rho^0) = -\frac{g'^2}{4\pi r}e^{-\lambda' r} + \frac{g'^2}{4\pi r}\frac{1}{2\kappa^2}\frac{d}{dr}\left(\frac{e^{-\lambda' r}}{r}\right)\vec{L}\cdot\vec{S}, \quad (1)$$

where g' is the coupling constant for the interaction of ρ^0 mesons and nucleons, λ' and κ are related to the ρ^0-meson mass μ' and the nucleon mass M as $\lambda' = \mu' c/\hbar$ and $\kappa = Mc/\hbar$, and we have used the Signell-Marshak definitions[3] of $\vec{L}$ and $\vec{S}$. The coefficient of $\vec{L}\cdot\vec{S}$ in (1) can be expressed as

$$V_{LS} = \frac{V^0}{x}\frac{d}{dx}\left(\frac{e^{-nx}}{x}\right), \quad (2)$$

with

$$V_0 = \frac{g'^2}{4\pi c\hbar}\,\frac{\lambda c\hbar}{2}\left(\frac{\lambda}{\kappa}\right)^2, \quad (3)$$

where λ is related to the pion mass μ as $\lambda = \mu c/\hbar$, while $x = \lambda r$ and $n = \mu'/\mu$.

According to our earlier ideas,[8] the ρ^0-meson mass should be somewhat larger than twice the pion mass, and the coupling constant for the interaction of ρ^0 mesons and nucleons should have the same value as the coupling constant for pions and nucleons. Thus, we can take

$$n \approx 2, \quad g'^2/4\pi c\hbar \approx 14. \quad (4)$$

We also have

$$\lambda/\kappa = 1/6.7, \quad \lambda c\hbar = \mu c^2 = 139.4 \text{ Mev}, \quad (5)$$

where we have taken the pion mass as $273 m_e$. Substituting the above values in (2) and (3), we find

$$V_{LS} = \frac{V_0}{x}\frac{d}{dx}\left(\frac{e^{-2x}}{x}\right), \quad (6)$$

with

$$V_0 = 21.7 \text{ Mev}. \quad (7)$$

It seems to us quite astonishing that not only (6) has exactly the same form as the latest phenomenological spin-orbit interaction of Signell, Zinn, and Marshak,[4] but our theoretical value of V_0 is also remarkably close to the phenomenological value of $V_0 = 21$ Mev.

It is tempting to conclude that the ρ^0 meson provides a complete explanation of the spin-orbit interaction between two nucleons. The resulting interaction also seems to be in agreement with the requirements of the shell model of the heavier nuclei.[10] It must, however, be noted that some objections have also been raised[11] against isotopic-spin-independent spin-orbit interactions, and at the present stage of our knowledge we cannot settle the problem of spin-orbit interaction with complete certainty. It is also possible that the ρ^0 meson is coupled less strongly to the nucleons than the pions, and that the spin-orbit interaction is partly due to the ρ^0 meson and partly due to pions.

*Supported in part by the National Science Foundation.

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V-A FOUR-FERMION INTERACTION AND THE INTERMEDIATE CHARGED VECTOR MESON*

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The universal V-A form of Fermi interaction seems to be compatible with the current experimental results.[1,2] In order to forbid many unwanted reactions, it has been speculated that the weak Fermi interactions are realized through the interaction of a charged current, J_α, with itself by exchange of a heavy charged boson.[1] The simplest possibility is the introduction of a charged vector meson B_α (with mass m_B) which is coupled to the J_α with the coupling constant F:

$$F J_\alpha B_\alpha + \text{H.c.} \tag{1}$$

The J_α may consist of the lepton currents, $\bar{e}\gamma_\alpha \times (1+\gamma_5)\nu$ and $\bar{\mu}\gamma_\alpha(1+\gamma_5)\omega$, and of the strangeness conserving and nonconserving baryon currents. We deliberately denote the neutral counterpart of the muon as ω. First of all, it may be remarked that the B_α-meson must be heavier than the K-meson.[3] The case when the B_α-meson is extremely heavy may not be realistic and there may be little point in introducing it. One interesting theoretical evidence against a B_α-meson which is not unreasonably heavy has been pointed out. Namely, if we take the two-component theory of the neutrino ($\nu \equiv \omega$) with lepton number conservation, the existence of the B_α would cause the $\mu \to e + \gamma$ transition.[4] It is, however, to be remembered that we could forbid this decay if we do not assume $\nu \equiv \omega$. For instance,[5] one may interchange the lepton number of μ^+ and μ^- and at the same time change the neutrino accompanying μ to an antineutrino[6] ($\omega \equiv \nu^C$). This possibility can hardly be differentiated from the usual theory by presently feasible experiments. In view of this situation, it may be worthwhile to investigate further the possible existence of a B_α-meson. In the following, unless mentioned, we neglect electromagnetic corrections. For the $\pi \to \mu(e) + \nu$ and $K \to \mu(e) + \nu$ decays nothing would be changed except for the replacement of the usual Fermi coupling constant G by $\sqrt{2}\, F^2/m_B^2$. For the K_{e3} and $K_{\mu 3}$ decays, however, the effect may be observable by future experiments. For instance, the general form of the matrix element of the K_{e3} mode is given (neglecting the electron mass) by

$$M F^2 \bar{e}(k\cdot\gamma)(1+\gamma_5)\nu(A - 2m_K E_\pi)^{-1}\phi_K(k)\,\phi_\pi(k-p), \tag{2}$$

where $A = m_B^2 - m_K^2 - m_\pi^2$. k_α and $k_\alpha - p_\alpha$ denote the energy-momentum four-vector of the K-meson and the pion, respectively. In principle, the effective coupling parameter M may depend on the total pion energy E_π. As M represents the contribution of baryon-antibaryon loops, this dependence is probably rather weak.[7] The denominator of (2) expresses the propagator of the B_α-meson. If the mass of the B_α-meson is not far removed from the K-meson mass, this denominator will behave as $-2m_K E_\pi$ [$A = 0$ if $m_B = (m_K^2 + m_\pi^2)^{1/2}$]. In this case the effect may be observ-