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TESTS FOR PARITY CONSERVATION IN THE
ELECTROMAGNETIC INTERACTION OF HADRONS

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ABSTRACT

Experimental limits on the possible coupling strength (ef) of a conserved hadronic axial current coupled to the photon are examined. The strongest limit, $f \leq 10^{-4}$, is deduced from the virtual photon contribution to the parity forbidden alpha decay of the 2^- excited of ^{16}O . The limit based on processes involving real photons is two orders of magnitude larger. Further experiments are suggested.

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The discovery of parity violation in the weak interactions demonstrated that reflection symmetry was not exact. It then remained an experimental problem to determine the extent to which parity conservation held for the strong and electromagnetic interactions. In this note we analyze the present status of such experiments involving the electromagnetic interaction of hadrons and discuss further experimental possibilities.

We first review the evidence for parity conservation in the strong interactions. Here the best evidence comes from the observation ¹⁾ of the parity forbidden alpha decay from the 2^- excited state of ^{16}O to the 0^+ ground state of ^{12}C . The parity violating width can be explained by an admixture of the order of 10^{-7} of neighbouring 2^+ states in the wave function of the excited ^{16}O ^{2),*)}. It seems reasonable that such a small admixture can be produced by the parity violating nucleon-nucleon force expected in the standard current-current theory of weak interactions. In particular only the $I = 0$ part of the weak nucleon-nucleon force is involved, which is expected to be dominated by ρ and ω exchange. While the $I = 0$ part does not vary too much from one weak interaction model to the other (in contrast to the $I = 1$ part), the calculation of the parity violating $\text{NN}\rho$ vertex from the current-current Hamiltonian is a subject of much controversy ³⁾. We shall take here the point of view that the strong interactions are parity conserving and that the strength of the $I = 0$ part of the parity violating weak force can be derived from the alpha decay experiment. This then requires ²⁾ that the $I = 0$ parity violating force has the strength of the order given by the simple factorization formula.

As a test of parity conservation in the electromagnetic interaction we consider the circular polarization P_γ in the reaction $n + p \rightarrow d + \gamma$ using thermal neutrons, measured ⁴⁾ to be $-1.30 \pm 0.45 \times 10^{-6}$. It is natural to consider that this result can also be explained by the parity violating weak nucleon force. An analysis ⁵⁾ shows that here too it is essentially the $I = 0$ part of the force that enters causing a small admixture of the 1P_1 state into the normal $^3S - ^3D_1$ deuteron wave function. Calculations ⁶⁾ using the same $I = 0$ force needed to explain the alpha decay give results at least

*) Extensive references on the calculation of parity violating effects are given in Refs. 2 and 3.

two orders of magnitude below the experimental result ^{*}). It should be emphasized that what is basically involved in both calculations is the weak interaction matrix element connecting a correlated di-nucleon S state to a di-nucleon p state. Thus in the comparison of the alpha decay result with that for $n+p \rightarrow d+\gamma$ the uncertainty is essentially in the nuclear wave functions ^{**}): In view of the serious discrepancy it is important that both theory and experiment be pursued further. However, if the present status of the theoretical and experimental results is accepted, one might conclude that parity violation in the electromagnetic interaction is the explanation of the large value of P_γ in $n+p \rightarrow d+\gamma$. Such a parity violation might also explain the disagreement ²⁾ between theory and experiment in the case of the circular polarization of the γ rays from ^{181}Ta , but in this case there are larger uncertainties in the nuclear wave functions and also the contributions of the $I = 1$ weak interaction, which depend on the weak interaction model, can be important.

In order to discuss how large such a parity violation might be it is necessary to look in more detail at a possible form of a parity violating electromagnetic interaction. We write

$$H_{e.m.} = e A^\lambda [j_\lambda + f k_\lambda] \quad (1)$$

where j_λ is the usual vector electromagnetic current and k_λ is a neutral axial hadronic current. In order to satisfy the small experimental limit on the value for the neutron electric dipole moment we assume that k_λ is even with respect to C so that the interaction with coupling ef violates P and C

^{*}) The only calculation ⁶⁾ that uses realistic potentials for the admixed P states and a parity violating potential that fits the α decay gives $P_\gamma = 3 \times 10^{-9}$. Other calculations ⁷⁾ agree in yielding a small value of P_γ as a result of the short range of the $I = 0$ force. The calculations allow for an admixture of 3P_0 into the initial continuum 1S_0 (in addition to the 1P_1 admixture in the deuteron) which may result from the $I = 2$ part of the weak interaction as well as the $I = 0$. The $I = 2$ force is also dominated by p exchange and is not expected to be more important than the $I = 0$ force so that it does not affect our qualitative discussion.

^{**}) The results also depend on the alpha decay matrix elements of different 2^+ states in ^{16}O and also on the spin dependence of the weak matrix element. If we consider only one admixed 2^+ state and only one of the two possible spin dependences, the predicted parity violating alpha decay still has the right order of magnitude whereas there is the large discrepancy for $n+p \rightarrow d+\gamma$. Therefore we feel that the problems of alpha decay matrix elements or of the spin dependence of the weak matrix element are not essential unless they produce a large accidental cancellation for the alpha decay.

but is CP invariant. We shall also make the assumption that k_λ is conserved. As a result it cannot be written in the simple form $\bar{p}\gamma_\lambda\gamma_5 p$, so that it becomes difficult to give any precise meaning to the factor f that measures the relative strength of the axial to the vector current ^{*)}. A parity violating direct coupling of hadrons to photons is expected to exist with a factor f of the order 10^{-5} to 10^{-6} as a consequence of the weak interactions ⁹⁾. The effect on P_γ of such a weak electromagnetic coupling are typically included among "exchange effects" or "off mass-shell effects" and have been calculated to make a contribution of 10^{-9} to 10^{-10} to P_γ ^{10), 11)}. It follows that if an interaction of the form (1) is to explain the value of P_γ of 10^{-6} it must have $f \sim 10^{-2}$ and must be interpreted as a parity violating electromagnetic interaction and not as a consequence of the usual weak interactions. We note also that, since the observation of P_γ depends on the transition between the 1S np continuum state and the deuteron state with the emission of an E1 gamma ray (interfering with the parity allowed M1 gamma ray), it is only the isovector part of the parity violating electromagnetic interaction that is involved.

The conclusion that a value of f as large as 10^{-2} is required to explain $P_\gamma \sim 10^{-6}$ is a consequence in part of the assumed current conservation, which forbids the parity violating emission of a real photon in a transition between nucleons on their mass-shell ⁹⁾. We turn to processes involving virtual photons. The general form of the matrix element of k_λ between nucleon states is ⁹⁾

$$\langle p' | k_\lambda | p \rangle = \frac{h(q^2)}{m_v^2} \bar{u}(p') [\gamma_\lambda q^2 - 2M q_\lambda] \gamma_5 u(p) \quad (2)$$

where m_v^{-1} can be considered as an effective axial charge radius and M is the nucleon mass. A parity violating force between nucleons as a result of photon exchange then has a matrix element of the form

$$\frac{e^2 f h(q^2) F_1(q^2)}{m_v^2} \bar{u}(p_1') \gamma_\lambda \gamma_5 u(p_1) \bar{u}(p_2') \gamma_\lambda u(p_2) \quad (3)$$

where F_1 is the usual nucleon electromagnetic form factor. A very similar parity violating nuclear force arises from the weak interactions for the case

^{*)} This problem and related problems that arise below are similar to those in theories with T violation in the electromagnetic interaction ⁸⁾.

$I = 0$ using factorization except $e^2 f/m_V^2$ is replaced by G^3). If we assume $h(0) = 1$ and $m_V \sim M$, then these two parity violating forces are equal in strength for $f \sim 10^{-4}$. Furthermore the range of this parity violating force due to photon exchange, like the $I = 0$ weak force, may be expected to be m_ρ^{-1} as a consequence of the contribution of the parity conserving nucleon electromagnetic vertex $^{*)}$. Since we have noted above that the parity violating electromagnetic vertex must have an isovector part, this may be combined with the isovector part of the usual electromagnetic nucleon vertex so that the isotopic spin dependence of the photon exchange term $^3)$ will include an $I = 0$ piece. Thus we find that the photon exchange has all the properties of the $I = 0$ weak force, and so the alpha-decay experiment can be used to limit f to a value of the order of or less than 10^{-4} .

Since we required a value of $f \sim 10^{-2}$ to explain $n + p \rightarrow d + \gamma$ and $f \leq 10^{-4}$ as a result of the alpha decay experiment, the introduction of parity violation in the electromagnetic interaction has not resolved the discrepancy between these experiments. Our discussion does indicate, however, that at the present time it is the virtual photon effect on the parity violating nuclear force manifested in alpha decay rather than experiments on the circular polarization of real photons that determines the best limit on f . In view of the difficulty of understanding the alpha decay and $n + p \rightarrow d + \gamma$ results in a consistent manner it seems worth while considering other tests of parity conservation in the electromagnetic interaction. We first consider elementary particle processes involving real photons :

(1) π^0 decay. The interaction (1) cannot contribute to $\pi^0 \rightarrow \gamma + \gamma$ since the interaction violates C , but it could produce the transition $\pi^0 \rightarrow 3\gamma$, which is as yet unobserved. This transition could also be produced by a C odd P even interaction $^8)$; in principle, the final states of 3γ for these two states are distinguishable by their angular and polarization correlations $^{12)}$.

(2) Σ^0 decay. Assuming even $\Sigma - \Lambda$ relative parity, the parity

$^{*)}$ There is no long range force associated with the photon exchange since as a result of current conservation there is no axial charge but only an axial charge radius. There are contributions of photon exchange other than that represented by Eq. (3), such as exchange of one π and one γ , but these should not change our qualitative conclusions.

violating matrix element of interest is

$$\langle \Lambda^0 | k_\lambda | \Sigma^0 \rangle = f \mu \bar{u}_\Lambda \sigma_{\lambda\nu} \gamma_\nu u_{\Sigma^0} q_\nu \quad (4)$$

Interference between (4) and a predominant parity conserving amplitude of order μ would show up in a net helicity of Λ in $\Sigma^0 \rightarrow \Lambda + \gamma$ and $\Sigma^0 \rightarrow \Lambda + e^+ + e^-$. Measurements of the effective mass spectrum of $e^+ e^-$ used in the determination of the relative $\Sigma - \Lambda$ parity provide a limit on f^2 ; present data ¹³⁾ indicate that less than 10% of the transition probability is due to a parity violating interaction. Since the form of Eq. (4) is forbidden by CP invariance for diagonal matrix elements it could be inhibited for the $\Sigma - \Lambda$ transition if simple SU(3) properties are assumed for k_λ .

(3) η decay. Parity violating effects in $\eta \rightarrow \pi^+ \pi^- \gamma$ have been discussed by Herczeg and Singer ¹⁴⁾. Because these effects are suppressed by angular momentum barriers they are expected to be no larger than 10^{-5} to 10^{-6} even if f is as large as 10^{-2} . The C violating charge asymmetry in $\eta \rightarrow \pi^+ \pi^- \gamma$ and the C violating one photon exchange process $\eta \rightarrow \pi^0 + e^+ + e^-$ ⁸⁾ can occur only with simultaneous CP violation. Therefore limits on these C violating effects are not relevant in limiting f .

(4) Pion photoproduction. Parity violation in the process $\gamma + p \rightarrow \pi^- + n$ could show up in the dependence of the cross-section on the circular polarization of the photon or on the nucleon polarization in the reaction plane. It could also show up for incident linearly polarized photons by the presence of a $\sin 2\varphi$ term in the pion angular distribution where φ is the angle between the normal to the reaction plane and the polarization direction. Henley et al. ¹⁵⁾ have calculated the circular polarization of the photon for the capture of pions at rest, $\pi^- + p \rightarrow \gamma + n$, due to the usual weak interaction and find a value between 10^{-7} and 10^{-8} ; it follows from their calculations that a value of f as large as 10^{-2} would yield in this process a circular polarization of 10^{-4} to 10^{-5} .

Parity violating effects could also show up due to virtual photon exchange in the elastic or inelastic scattering of muons or electrons from nucleons at large q^2 . The simplest effects are a dependence of the cross-section on the helicity of the incident lepton or on the nucleon polarization in the reaction plane ¹⁶⁾. Such effects are expected as a result of the usual weak interaction to have a value of the order $10^{-6} g^2$, where g^2 is given in $(\text{GeV})^2$ ⁹⁾. Effects of the order $10^{-4} g^2$ are expected as a result of neutral currents in the Weinberg theory ¹⁷⁾ where the parity violating interaction has

a coupling G in contrast to an effective coupling $e^2 G$ in the usual theory with charged currents only. The parity violating effects associated with the current k_λ discussed here will be of the order $f g^2/m_V^2$ and thus comparable to those in Weinberg's theory if $f \sim 10^{-4}$. There is a qualitative distinction between the two predictions : the parity violating effect due to k_λ involves the product of an electron vector (V) current with a hadron axial (A) current whereas a major part of the parity violating effect in Weinberg's theory (the only effect if $\sin^2 \theta_w = \frac{1}{4}$) involves the product of an electron A current with a hadron V current. An experimental consequence of this distinction is that the parity violating effects due to k_λ do not change when $e^-(u^-)$ is replaced by $e^+(u^+)$ whereas they would be expected to change in the Weinberg theory. Still larger parity violating effects are expected in these processes for some other weak interaction theories with neutral currents¹⁸⁾. Thus the absence of parity violating effects in electron or muon scattering may be used to put limits on electromagnetic parity violation but their presence might have other explanations. Similar remarks can be made concerning parity violating effects in e^+e^- annihilation¹⁹⁾.

The parity violating nuclear force associated with virtual photon exchange Eq. (3) could also be studied more directly in polarized proton-proton scattering. The weak interaction effects associated with ρ and ω exchange are expected to give an asymmetry of the order 10^{-6} to 10^{-7} ²⁰⁾; the observation of an asymmetry at this level could then be used as in our discussion of alpha decay to limit f to 10^{-4} .

In this note we have explored the experimental consequences of a CP invariant parity violating electromagnetic current for hadrons. We have considered only a conserved current and we have assumed that the only other parity violation is of the order given by the weak interaction. It should be emphasized that there is no theoretical demand for such a current and it should not be confused with the possibility of a non-electromagnetic parity violation of order α that has been discussed in connection with renormalizable theories of the weak interaction. From experiments in which real photons are emitted we conclude that a parity violating interaction 10^3 greater than that induced by the weak interactions is not ruled out and on this basis we would allow a value of $f \sim 10^{-2}$. On the other hand we have found that better evidence against such parity violation comes from the virtual photon contribution to the forbidden alpha decay of the 2^- state of ^{16}O , from which we concluded $f \lesssim 10^{-4}$. These conclusions are extremely qualitative since the parameter f has not been defined in terms of a single model. In any case

in view of the difficulty in understanding consistently all experiments on parity violation using nuclei we believe that tests of parity conservation using elementary particle experiments such as pion photoproduction, Σ^0 decay, and electron-proton scattering should be considered.

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