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# Electromagnetic Parity Violation for Hadrons

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It is argued that a first-order weak direct parity-violating electromagnetic interaction should exist for hadrons. The interaction vanishes for real photons if the initial and final hadrons are identical and if off-mass-shell effects are neglected; the interaction contributes to reactions where this is not the case or for virtual photons. Estimates of the magnitude of parity-violating effects are made for nuclear electromagnetic transitions and for electron-proton elastic scattering. It is shown that asymmetries $\approx 10^{-6} - 10^{-5}$ can be expected in 20-GeV elastic electron scattering from polarized protons.

Parity violation in nuclei is now a well-established phenomenon.[1] However, the observed circular polarizations of photons emitted in heavy nuclei appear to be more than an order of magnitude larger than those predicted by applications of the standard Cabibbo theory.[2] On the other hand, the magnitude of the parity-violating (PV) $\alpha$ decay rate[3] of the $2^-$ state in $^{16}O$ is in reasonable agreement with the calculated value.[4] Various explanations have been advanced[5] to explain the discrepancy, but the effects considered are generally too small. Here we examine the effect of a direct parity-violating electromagnetic interaction[6] and suggest experiments to detect its presence.

There are a number of reasons that a first-order weak direct PV electromagnetic interaction of hadrons can be expected. Foremost among these is the fact that a weak coupling of neutral vector mesons to nucleons is predicted with a variety of models. A PV electromagnetic interaction then follows from vector dominance or field-current identity. In $SU(6)_W$ (Ref. 7) and in the $\sigma$ model[8] such couplings are of order $f \approx \lambda G m_V{}^2 \cos^2\theta\, g_{VN}{}^{-1} \approx 10^{-6}$, where $G$ is the weak coupling constant, $\lambda$ is the axial-vector renormalization constant, $g_{VN}$ is the vector-meson-nucleon coupling constant, $m_V$ is the mass of the vector boson, and $\theta$ is the Cabibbo angle. The PV two-pion-exchange force[9] proportional to $\sin^2\theta$ may also have an effective $\rho^0$ contribution, but since this coupling is reduced by $\tan^2\theta \approx \frac{1}{20}$ we shall neglect it. A weaker reason for conjecturing a direct PV electromagnetic interaction is that simple models are unable to predict the large PV amplitude found experimentally in the decay $\Sigma^+ \to p\gamma$.[10]

The most general form of a PV electromagnetic current for particles of spin $\frac{1}{2}$ is

$$\langle b|J^\mu_{\rm PV}|a\rangle = ef\bar{u}_b(p')\left(\gamma^\mu h_1 + \frac{q^\mu}{2M}h_2 + i\sigma^{\mu\nu}\frac{q_\nu}{2M}h_3\right)\gamma^5 u_a(p)\,. \qquad (1)$$

We have omitted isospin factors in Eq. (1); $ef$ is an effective coupling of order $10^{-6}e$, and $h_1$ is a form factor which is a function of the photon momentum squared $q^2$ for baryons on their mass shells. If $\epsilon_\mu$ is the polarization vector for a real photon, then $\epsilon_\mu q^\mu = q^2 = 0$, and it follows from Eq. (1) that $h_1(0) = 0$ and $h_2$ does not contribute. In a theory which is $CP$-invariant $h_3$ must vanish if $a$ and $b$ are identical particles on their mass shells; time-reversal invariance requires that $h_3$ be real if $a$ and $b$ differ as in $\Sigma^+ \to p\gamma$. Of course, real photons cannot be emitted if $a$ and $b$ are the same particle on its mass shell.

As a first application we consider electromagnetic transitions in nuclei. To the extent that an impulse approximation is valid and that the electromagnetic transition operator is a sum of single-nucleon ones considered to be on their mass shells, it follows that no PV electromagnetic effect can occur. However, off-mass shell effects and exchange contributions can alter this conclusion. From a different point of view, we can treat the initial ($a$) and final ($b$) nuclear states as independent particles. If we take these states to have spin $\frac{1}{2}$ for simplicity, then a term such as

$$\langle b\gamma | H_{PV}^{eff} | a\rangle = \frac{ef}{2M}\bar{u}_b i\sigma^{\mu\nu} q_\nu \gamma^5 u_a h_3(q^2, m_a^2, m_b^2)\epsilon_\mu$$

$$\approx ef\frac{q}{2M}\vec{\sigma}\cdot\vec{\epsilon}h_3 \qquad (2)$$

can occur. We expect $h_3$ to be reduced relative to unity by off-mass-shell effects of order $m_\pi/M$, or more likely, $V/M \approx 0.04$, where $V$ is of the order of the depth of a nuclear potential. The effective PV electromagnetic coupling would thus be of order $efh_3 \approx 4\times 10^{-8}e$, which is too small to explain the experimental-theoretical discrepancy referred to earlier unless a coherence factor (e.g., $Z$, the nuclear charge number) occurs. This seems unlikely because of the spin dependence of Eq. (2); however, a certain degree of coherence is possible for collective transitions. It should be noted that, to leading order, the operator of Eq. (2) behaves like an $E1$ multipole operator, but is directly proportional to the spin part of the standard $M1$ operator. Thus, whatever dynamical effects reduce the parity-allowed $M1$ matrix element will also usually affect the PV $E1$ matrix. For the 482-keV transition of $^{181}$Ta, the above source of parity violation would thus predict a circular polarization $\lesssim 10^{-7}$, which is more than an order of magnitude smaller than experiment.[1] Although off-shell effects are probably smaller in deuterium than in other nuclei, the above prediction for the circular polarization in thermal $n$-$p$ capture is of the same order as that computed by standard considerations.[11] Furthermore, the predicted asymmetry in the photon distribution from the capture of polarized neutrons is even somewhat larger than previously predicted.[11]

As a different application and as a test of our suggestion, we consider next the case when $a$ and $b$ are both free nucleons in Eq. (1) but the photon is virtual, as in electron-proton scattering. In that case, it follows from current conservation, $q_\mu J_{PV}^\mu = 0$, where $J_{PV}^\mu$ is the electromagnetic current of the proton, that $J_{PV}^\mu$ may have the form

$$\langle a| J_{PV}^\mu | a\rangle = \frac{ef}{m_V^2}\bar{u}(p')(\gamma^\mu q^2 - 2Mq^\mu)\gamma^5 u(p) h(q^2), \qquad (3)$$

where $m_V$ is the mass of the vector meson. We have assumed that $J_{PV}^\mu$ is regular in the limit $q^2 \to 0$. We obtain Eq. (3) if we assume vector dominance and a weak PV $\rho^0$ and $\omega^0$ coupling to nucleons as

$$\langle NV | H_{PV} | N\rangle = f m_V^{-2}\bar{u}(p')\gamma^\mu\gamma^5 u(p)\Box V_\mu , \qquad (4)$$

with $f \approx 10^{-6}$ in both Eqs. (3) and (4). The D'Alembertian form of the coupling in Eq. (4) gives the usual result for real vector mesons or for the PV vector-meson-exchange potential. We take $h(q^2)$ to be the normal dipole form factor $= (1 - q^2/0.71)^{-2}$, if $q^2$ is measured in units of GeV$^2/c^2$. Thus, in this case, we predict parity-violating effects of order $fq^2/m_V^2$, which can be sizable for reasonably large $q^2$. It follows from Eq. (3) that there is no long-range (e.g., Coulomb) PV force, but there is a short-range one.

We consider the elastic scattering of high-energy electrons by polarized protons. The electromagnetic currents of the proton are taken to be the sum of the normal current $J^\mu$ together with $J_{PV}^\mu$, i.e., $\mathcal{J}^\mu = J^\mu + J_{PV}^\mu$, with

$$\langle a| J^\mu | a\rangle = \bar{u}(p')\left[\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}\kappa F_2(q^2)\right]u(p), \qquad (5)$$

where $\kappa = 1.79$ is the anomalous magnetic moment of the proton, and $F_1(0) = F_2(0) = 1$.

With the given currents and the standard electromagnetic interaction for electrons,[12] we obtain for the asymmetry $A$ in the laboratory system

$$A_{lab} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{q^2}{m_V^2} fh\{G_M M(E^2 + E'^2\cos\theta)(1 - q^2/4M^2) + \tfrac{1}{2}(G_E - G_M)(E + E')[E(M - E') + E'\cos\theta(M + E)]\}$$

$$\times[(G_E^2 - G_M^2 q^2/4M^2)\cos^2(\tfrac{1}{2}\theta) - G_M^2(1 - q^2/4M^2)(q^2/2M^2)\sin^2(\tfrac{1}{2}\theta)]^{-1}, \qquad (6)$$

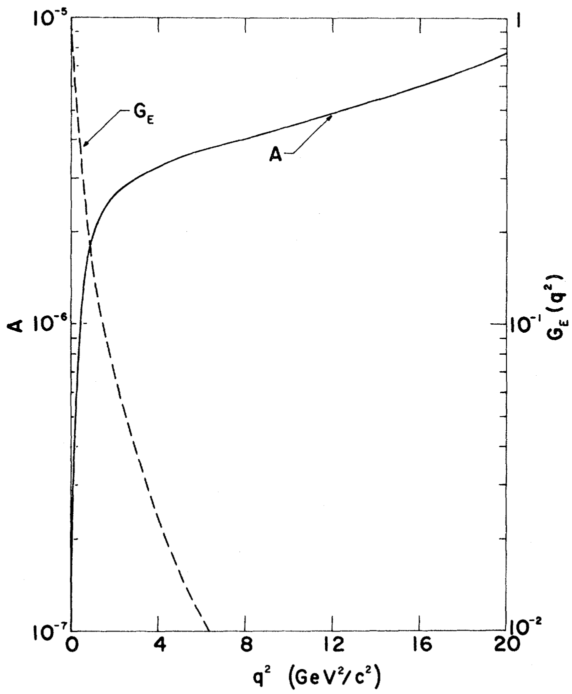


FIG. 1. Asymmetry, $A(q^2)$, for elastic electron-proton scattering. The form factor $G_E = (1 - q^2/0.71)^2$ is shown for comparison purposes.

where $E$ and $E'$ are the initial and final electron energies, respectively, and $\theta$ is the laboratory scattering angle. In Eq. (6) $G_E$ and $G_M$ are the usual[12] form factors for the proton, and $\sigma_\uparrow, \sigma_\downarrow$ are the cross sections for protons polarized parallel and antiparallel to the direction of the incident electrons. The asymmetry $A$ is plotted as a function of $q^2$ in Fig. 1. It can be seen that the asymmetry is roughly given by $fq^2/2m_p^2$. The asymmetry predicted by Eq. (6) is uncertain, however, up to a factor which may be as large as an order of magnitude. The weak coupling constant $f$ is unknown and may even be as large as $10^{-5}$.[13] Although the magnitude of the asymmetry increases with momentum transfer, the differential cross section decreases much more rapidly; for large $q^2$, $d\sigma/d\Omega$ is roughly proportional to $q^{-10}$. We show $G_E(q^2)$ in Fig. 1 for purposes of comparison. The $q^2$ dependence of the form factors cancels in Eq. (6) because we assumed the same dependence for $h$, $G_E$, and $G_M$, but this cancellation does not occur in the differential cross section. Thus, the maximum counting rate actually occurs for modest values of $q^2$, and this makes the experimental detection of the effect in elastic scattering difficult. The asymmetry should, however, also be present in inelastic scattering, e.g., inclusive reactions, where the cross section does not fall as rapidly with increasing $q^2$.

We have briefly examined the consequences of the PV electromagnetic force proposed here for some atomic phenomena,[14] but have found that the effects considered, e.g., in the Lamb shift, are too small to be measurable.

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# Errata

**Octet Pomeranchukon Component and Absorption in Hypercharge-Exchange Reactions,** P. J. O'Donovan and T. E. Prickett [Phys. Rev. D 6, 1995 (1972)]. In the relation for $\pi^- p \to K^0 \Lambda$ in Eq. (3), the factor $(C_1 - \frac{4}{3}C_2)$ should read $C_1$; relations (4b) and (4d) should be altered accordingly. With this correction, $C_2/C_1$ from the 3.9-GeV/$c$ relation (4b) is small and positive ($\sim 0.1$) for $-t < 0.1$ (GeV/$c$)$^2$ and small and negative ($\geqslant -0.2$) for $-t > 0.1$ (GeV/$c$)$^2$. Relation (4d) for $f = 1.2$ is virtually unchanged from that shown in Fig. 1(b). The conclusions of the paper are unaffected.

**Simplified Regge Analysis of Backward $\pi^+ p$ Scattering,** S. Kogitz and R. K. Logan [Phys. Rev. D 6, 2028 (1972)]. The 6-GeV/$c$ data displayed in Fig. 3 are erroneously identified as coming from the experiment of Schneider *et al.* They in fact come from Boright *et al.*, Phys. Rev. Letters 24, 964 (1970).