Effective neutral current and parity violation in the scattering of high energy protons

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The P-odd effects calculated within the framework of a theory with charged currents with allowance for the exchange (annihilation) of the constituent partons, constitute 0.3×10^{-7} of the total cross section in the case of the scattering of protons with $E_{\rm lab}\approx 10$ GeV, reach 10^{-6} at $t\sim s$, and increase in power-law fashion with increasing $E_{\rm lab}$.

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The problems connected with weak interactions of hadrons are attracting ever increasing interest because of the advent of intense beams of polarized protons, which are needed for the registration of weak parity-violation effects.[1,2] In the present article, the P-odd effects in the scattering of high-energy protons are considered from the point of view of the parton model, within the framework of which there appears in natural fashion an "effective" neutral current due to exchange or annihilation of the constituent partons, and where, violating parity, the amplitude of the weak interaction (in this case elastic scattering of the hadrons) does not decrease with increasing energy.

It is proposed in this article that the weak-interaction Lagrangian of the partons is made up only of charged currents. The truly neutral current observed in the interaction of the neutrinos with the nuclei seems to conserve parity, since the ratio $\sigma_{\nu A\to\nu\ldots}/\sigma_{\nu A\to\ldots}$ is close to unity.[3] In any case, the parity-violation effects connected with it can be added to the calculations below.

It was shown earlier[4] that in reactions with charge exchange the dominant factor in reactions with charge exchange in the amplitude of the weak interaction at high energies is exchange of the intermediate vector boson $W^{\pm}$ (Fig. 1). This statement is valid at $|t|\leq\mu^2$ if the principal role in the scattering of high-energy hadrons is played by multiperipheral processes, and at $t\sim s$[5] if the large-angle hadron scattering reduces to

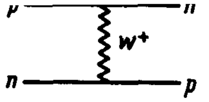

FIG. 1.

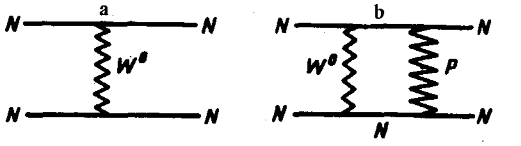

FIG. 3.

the scattering of valence partons.[6] In either case, the weak effects increase in power-law fashion with increasing energy and momentum transfer.[4,5,7]

The mechanism for the onset of an effective neutral current due to exchange or annihilation of the constituent partons[5] is illustrated in Fig. 2. It is based on the fact that for pointlike objects such as partons the amplitude of scattering without change of charge does not contain a special small quantity (cf. νe and νe scattering). The corresponding amplitude for hadron scattering can be represented at $s < m^2_{W_\pm}$ (formally) as exchange of neutral vector bosons W^0 (Fig. 3) with isotopic spins zero and unity, and with form factors W^0NN known from the scattering of leptons by nucleons. The axial isoscalar form factor can be obtained in principle (within the framework of a model of the Weinberg type) from a comparison of the data on νN and νe scattering. The parity-violating amplitude of elastic proton-nucleon scattering as a result of exchange of the constituents can be written in the form

$$M_{\bar{W}} = \frac{G}{\sqrt{2}}\left\{\bar{u}_3\left[f_1(t)\gamma_\mu - f_2\frac{\sigma_{\mu\lambda}q_\lambda}{2m}\right]u_1\bar{u}_4\gamma_\mu\gamma_5u_2 + \bar{u}_3\gamma_\mu\gamma_5u_1\bar{u}_4[f_1(t)\gamma_\mu + f_2(t)\sigma_{\mu\lambda}q_\lambda/2m]u_2 - \begin{pmatrix}1\to 2\\ t\to u\end{pmatrix}\right\} \quad (1)$$

$G = 10^{-5}\ m^{-2}$; m is the mass of the nucleon, and $t = q^2 < 0$. The functions $f_1(t)$ and $f_2(t)$ are expressed in terms of the vector and axial form factors $F^{0,1}_{1,2}(t)$ and $G^{0,1}(t)$, where the superscript denotes the isotopic spin. (The electromagnetic vertex of the nucleon takes the form $\bar{u}(F_1\gamma_\mu - F_2\sigma_\mu\lambda q_\lambda/2m)u$, where $F_1 = (F_1^0 + \tau_3F_1^1)/2$; a similar expansion can be obtained for F_2 and $G^{0,1}$.)

$$f_1 = -\frac{1}{2}(3F_1^0G^0 - \tau_3F_1^1G^1), \quad f_2 = -\frac{1}{2}(3F_2^0G^0 - \tau_3F_2^1G^1) \quad (2)$$

τ_3 is double the projection of the target-nucleon isospin. In the case of exact $SU(3)$ symmetry we have $G^0_{t=0} = (3/5)G^1_{t=0}$ (if we neglect the contributions of the strange partons at the vertex of the interaction of W_0 with the nucleons). Experiment yields $G^1 = 1.25 \pm 0.09$. Using the standard dipole parametrization for $F_{1,2}$ and $G^{0,1}$, as well as the values

$$F_1^0|_{t=0} = 1 = F_1^1|_{t=0}, \quad F_2^0(0) = \mu_s \text{ and } F_2^1(0) = \mu_v,$$

where $\mu_v = \mu_p - \mu_n$ and $\mu_s = \mu_p + \mu_n$ (μ_p and μ_n are the anomalous magnetic moments of the proton and neutron) we can obtain the following expressions for $f^p_{1,2}(t)$ and $f^n_{1,2}(t)$—for pp and pn scattering, respectively

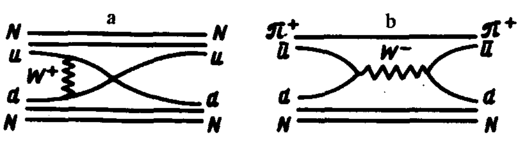

FIG. 2.

$$f_1^p = \frac{G^1}{2}\left\{-\frac{4}{5} - \frac{t}{4M^2}\left(\mu_v - \frac{9}{5}\mu_s - \frac{4}{5}\right)\right\}D(t), \quad f_2^p(t) = \frac{G^1}{2}\left\{\mu_v - \frac{9}{5}\mu_s\right\}D,$$

$$f_1^n = -\frac{G^1}{2}\left\{\frac{14}{5} - \frac{t}{4M^2}\left(\frac{14}{5} + \mu_v + \frac{9}{5}\mu_s\right)\right\}D \qquad f_2^n(t) = -\frac{G^1}{2}\left(\mu_v + \frac{9}{5}\mu_s\right)D, \quad (3)$$

$$D^{-1} = (1 - t/4m^2)(1 - t/0.71)^2(1 - t/m_A^2)^2, \quad m_A^2 = 0.9 \pm 0.2\ \Gamma\text{GeV}[8].$$

If the quarks are colored, then all the form factors contain an additional factor 1/3. The contribution from the effective neutral current to the difference $\sigma_+ - \sigma_-$ of the total cross sections for the scattering of protons polarized along and against their momentum, arises from the interference of the amplitude (1) with the real part of the strong amplitude (as the imaginary part of diagrams of the type of Fig. 3, which describes the screening of the weak interaction). We estimate the value of $\bar{r} = (\sigma_+ - \sigma_-)/\sigma$ in the eikonal approximation (Fig. 3b)

$$\bar{r} = +G\frac{\eta\, 0.9G^1}{4\pi\sqrt{2}(\lambda_s + \lambda_W)}. \quad (4)$$

Here $\eta = \mathrm{Re}f_s/\mathrm{Im}f_s|_{t=0}$, while λ_s and λ_W are the slopes of the amplitudes of the strong and weak interactions. At $E_{\mathrm{lab}} \sim 10$ GeV we have $\lambda_s + \lambda_W = 10\ \mathrm{GeV}^{-2}$. At $E = 6$ GeV ($\eta = -0.3$)[9] we obtain $\bar{r} = 0.3\times10^{-7}$. Experiment yields $\bar{r} < 10^{-5}$.[1] We note that $G < 0$ and $\bar{r} > 0$ if the weak interaction is indeed effected via an intermediate boson. The earlier estimates for r at energies up to several hundred MeV, using the standard ideas concerning the exchange of ρ, ω, 2π and a number of other hypotheses, are also in the region of 10^{-7}.[10–13] It should also be noted that there is no smallness of η if one measures a correlation of a more complicated type $[\vec{\sigma}_i\times\mathbf{n}]\cdot\vec{\sigma}_f$, i.e., if one investigates the dependence of the total cross section on the transverse polarization of the beam ($\vec{\sigma}_i \perp \mathbf{n}$) for a transversely-polarized target ($\vec{\sigma}_f \perp \mathbf{n}$, $\vec{\sigma}_f \perp \vec{\sigma}_i$). There is also a contribution from the renormalization of the vertex of the vacuum pole as a result of the weak interaction. It can be separated in principle by using targets with different numbers of protons and neutrons.

Let us proceed to estimate the P-odd effect at $t \sim s$, assuming that scattering of valent partons predominates and that it is possible to use expression (1) for the pp scattering amplitude. The upper limit of the quantity

$$r_{t\sim s} = \left(\frac{d\sigma_+}{dt} - \frac{d\sigma_-}{dt}\right)\Big/\frac{d\sigma}{dt}$$

can be obtained from the formula

$$r_{\max} = 4\sqrt{\frac{d\sigma^W}{dt}\Big/\frac{d\sigma_s}{dt}},$$

where $d\sigma_s/dt$ is known from experiment,[14] and $d\sigma^W/dt$ is the cross section due to the P-odd weak-interaction amplitude (1):

$$\frac{d\sigma^W}{dt} = \frac{G^2}{4\pi}\left[\left(f_1(t) + f_2(t)\sin^2\frac{\theta}{2} + f_1(u) + f_2(u)\cos^2\frac{\theta}{2}\right)^2 + \frac{E^2}{4m^2}\sin^2\theta\left(f_1(t) - f_2(u)\right)^2\right] \quad (5)$$

E and θ are the energy and scattering angle of the proton in the c. m. s. For scattering at $p_{lab} = 12.5$ GeV/c and $|t| = 6$ GeV^2 we obtain $r_{max} = 10^{-6}$. In the case colored quarks $r_{max} \approx (1/3)\times 10^{-6}$. The value of r depends on the spin structure of the strong amplitude and its phase. If $f_s(t\sim s)$ is determined by the scattering of partons with exchange of say, a vector gluon, then $f_s(t\sim s)$ is real and r is close to r_{max}.

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