ISOTOPIC AND CHIRAL STRUCTURE OF NEUTRAL CURRENT

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Relations are obtained between the cross sections for ν and $\bar{\nu}$ scattering by nuclei; these relations explain the isotopic and chiral structure of the neutral current. It is show that the cross section for the interaction of low-energy neutrinos is enhanced by the coherence effect, and processes in which charged current participates are suppressed by virtue of the Pauli principle.

In the theoretical analysis of total cross sections we shall use the parton-quark model [1]. We neglect the contribution of the antipartons, since $\sigma(\bar{\nu}A \to \mu + \ldots)/\sigma(\nu A \to \mu + \ldots) = 0.38 \pm 0.02$ [2], which is close to $(1/3)(A + Z)/(2A - Z) \simeq 1/3$, the value expected when the contribution of the antipartons is discarded [1]. (Here Z and A - Z are the numbers of protons and neutrons in the nucleus). The Hamiltonian of the weak interaction of neutrinos with quarks is

$$H = \frac{G}{\sqrt{2}} \bar{u}_\nu \gamma_\mu (1 + \gamma_5) u_\nu j^h_\mu .$$

The strangeness-conserving neutral current can we written in the most general form as

$$j^h_\mu = \bar{q}_p \gamma_\mu (\kappa_p + \gamma_5) q_p + a \bar{q}_n \gamma_\mu (\kappa_n + \gamma_5) q_n + \beta \bar{q}_\lambda \gamma_\mu (\kappa_\lambda + \gamma_5) =$$

$$= \bar{q} \left\{ \zeta \lambda_3 (\kappa_3 + \gamma_5) + \eta \frac{\lambda_8}{\sqrt{3}} (\kappa_8 + \gamma_5) + \frac{\gamma}{-3} \lambda_0 (\kappa_0 + \gamma_5) \right\} q . \tag{1}$$

Here $\lambda_3/2$, $\lambda_8/\sqrt{3}$, and $\lambda_0/3$ are the isospin, hypercharge and baryon-number matrices for the quarks.

For V - A neutral current, i.e., $\kappa_p = \kappa_n = 1$ we have for scattering by a nucleus with an arbitrary number of protons and neutrons

$$\frac{\sigma(\bar{\nu} A \to \bar{\nu} + ..)}{\sigma(\nu A \to \nu + ..)} = \frac{1}{3} . \tag{2}$$

In the Feynman - Gell-Mann theory of universal weak interaction, in which only charged V - A currents exist in the lowest approximation in the weak interaction, the neutral currents result from the higher orders in the weak interaction. In this case, neutral currents of the V - A type are also noticeable [3]. A disparity with the experiment (2) would therefore denote that the observed neutral currents are of a different origin. Preliminary experimental data on the scattering of neutrinos and antineutrinos by nuclei [2, 4] point to a violation of the relation (2):

$$\frac{\sigma(\bar{\nu}A \to \bar{\nu} + ..)}{\sigma(\nu A \to \nu + ..)} = 0{,}8 \pm 0{,}3 \,; \tag{3}$$

We denote by R_{ν}^{A} and $R_{\bar{\nu}}^{A}$ the ratio of the total ν and $\bar{\nu}$ scattering cross sections on account of the neutral and charged currents. Using (1), we express R_{ν}^{A} and $R_{\bar{\nu}}^{A}$ in terms of G', α, κ_p, and κ_n:

$$R_{\nu}^{A} = \left(\frac{G'}{G}\right)^2 \frac{\{Z[2(1+\kappa_p^2 \;\; \kappa_p) + a^2(1+\kappa_n^2+\kappa_n)] + (A-Z)[(1+\kappa_p^2+\kappa_p) + 2a^2(1+\kappa_n^2+\kappa_n)]}{3(2A-Z)\cos^2\theta}, \tag{4}$$

$$R_{\bar{\nu}}^{A} = \left(\frac{G'}{G}\right)^2 \frac{\{Z[2(1+\kappa_p^2-\kappa_p) + a^2(1+\kappa_n^2-\kappa_n)] + (A-Z)[1+\kappa_p^2-\kappa_p) + 2a^2(1+\kappa_n^2-\kappa_n)]}{(A+Z)\cos^2\theta}. \tag{5}$$

In the derivation of (4, 5), the quarks were assumed massless and we used the following relations from [5]:

$$\frac{\sigma(\nu p \to e^- + ..)}{\sigma(\nu n \to e^- + ..)} = \frac{1}{2}, \qquad \frac{\sigma(\bar{\nu} p \to e^+ + ..)}{\sigma(\bar{\nu} n \to e^+ + ..)} = 2\,. \tag{6}$$

In Weinberg's model [6], in which the fundamental spinors are e, ν_e, μ, and ν_μ for leptons and the quarks q_p and q_n for hadrons we have $G' = G\cos\theta/2$, $\kappa_p = 1 - (8/3)\sin^2\phi$, $\kappa_n = 1 - (4/3)\sin^2\phi$, and $\alpha = -1$, where ϕ is the Weinberg mixing angle [6] and θ is the Cabibbo angle.

It is interesting that at $\sin^2\phi = 0.375$ we have $R_{\nu}^{A} = 0.22$ and $R_{\bar{\nu}}^{A} = 0.42$ for freon, which agrees with $R_{\nu}^{A} = 0.22 \pm 0.03$ and $R_{\bar{\nu}}^{A} = 0.45 \pm 0.09$ [4].

We now consider interactions between low-energy neutrinos ($E_\nu \ll M_N$) and nuclei, where coherent scattering is possible in the case of the neutral current if $q^2 \lesssim 1/R^2$. (Here q is the momentum transfer and R is the radius of the nucleus). We have

$$\left.\frac{d\sigma}{d\Omega}\right|_{\nu A \to \nu \ldots} = \left.\frac{d\sigma}{d\Omega}\right|_{\bar{\nu} A \to \bar{\nu} \ldots} = \frac{G'^2 E_\nu^2}{4\pi^2}\{F_\nu^2(1+\cos\delta) + F_A^2(3-\cos\delta)\}. \tag{7}$$

In (7), δ is the scattering angle in the laboratory system. We express $F^{\nu'}$ in terms of the parameters of the initial Hamiltonian (1) for an arbitrary nucleus:

$$F^\nu = \zeta\kappa_3(2Z-A) + (\eta\kappa_8 + \gamma\kappa_0)A. \tag{8}$$

In Weinberg's model [6] we have $\zeta\kappa_3 = 1 - 2\sin^2\phi$, $\eta\kappa_8 = -2\sin^2\phi$, $\gamma = 0$, and F^A depends on the structure of the nuclear shell. For He^4 we have $F_A = 0$. For D^2 we express $(F_A)^2$ in terms of the axial constants of the proton and the neutron:

$$(F_A)^2_{D^2} = \frac{2}{3}(g_{A_p} + g_{A_n})^2 + \frac{1}{3}(g_{A_p} - g_{A_n})^2. \tag{9}$$

Here $g_A = G_A'/G$ and $g_{A_p} + g_{A_n} = 2(\eta+\gamma)/3$. To calculate $g_{A_p} = -g_{A_n}$ we use the nonrelativistic quark model [7]: $g_{A_p} = -g_{A_n} = (10/3)\zeta$.

Let us estimate the kinetic energy of the nucleus, which must be registered in order to observe coherent scattering: $T = (q^2/2M) \leq 4/2mR^2$. (We express the nuclear form factor in the form $\exp(-q^2R^2/4)$.) For He^4 we have $R_{He^4} = 1.6$ F and consequently $T \leq 8$ meV; for C^{12} we have $R_{C^{12}} = 2.5$ F and $T \leq 1$ meV.

In the case of charged current, there is hindrance for scattering by a bound nucleon at small momentum transfers, owing to the Pauli principle. For example, for a deuteron at $q^2 \ll R^{-2}$:

$$\frac{\dfrac{d\sigma}{d\Omega}\,\nu d \to e^- pp}{\left.\dfrac{d\sigma}{d\Omega}\right|_{\nu n \to e^- p}} = \frac{\frac{1}{3} g_A^2}{1 + g_A^2} \approx 0{,}23. \qquad (10)$$

Here $g_A = G_A/G$.

In the case of a closed nuclear shell, the cross section vanishes at $q^2 \ll R^{-2}$, e.g. for He^4 and O^{16}. The hindrance factor for C^{12} was calculated in [8] and is approximately equal to 3. The cross section for scattering by the nucleus is only double the cross section for scattering by a free neutron.

Note. After submission of this letter to the article, the authors learned of a paper by R. B. Palmer (Phys. Lett. 46B, 240, 1973), in which the interaction of high-energy neutrinos with nucleons is considered in the quark parton model (of Weinberg) and agreement with experiment [4] is obtained.

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[1] R. P. Feynman, Photon-Hadron Interactions, Benjamin, 1972; J. D. Bjorken and E. A. Pashos, Phys. Rev. D1, 3151 (1970).
[2] T. Eichten et al., CERN Preprint, 1973; A. C. Benvenuti et al. Phys. Rev. Lett. 30, 1084 (1973).
[3] B. L. Ioffe and E. P. Shabalin, Yad. Fiz. 6, 828 (1967) [Sov. J. Nuc. Phys. 6, 603 (1968); M. Gell-Mann, N. Kroll, and F. Low, Phys. Rev. 179 , 1518 (1968).
[4] F. J. Hasert et al., Phys. Lett. 46B, 138 (1973).
[5] M. Gourdin, Nucl. Phys. B53, 509 (1973).
[6] S. Weinberg, Phys. Rev. D5, 1412 (1972).
[7] E. M. Levin and L. L. Frankfurt, Usp. Fiz. Nauk 94, 243 (1968) [Sov. Phys.-Usp. 11, 106 (1968)]
[8] J. S. Bell and C. H. Llewellyn-Smith, Nucl. Phys. B28, 317 (1971).