PHYSICAL REVIEW D VOLUME 23, NUMBER 3 1 FEBRUARY 1981

Possible spin-3/2 quarks and scaling violations in neutrino reactions

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(Received 19 September 1980)

The relevance of possible spin-3/2 fundamental fermions in connection with models of subquark structure is discussed. The Bjorken limit for production of spin-3/2 partons is investigated and the departures from the well-known spin-1/2 behavior are examined. The pattern of scaling violation for these processes can be clearly separated from the predictions of quantum chromodynamics.

Since the discovery of the τ (Ref. 1) and the Υ (Ref. 2) a remarkable symmetry between quarks and leptons has seemed to emerge. In the standard model[3] of unified weak and electromagnetic interactions, to each leptonic family there corresponds a quark family. Even if the experimental evidence for the top quark and the τ neutrino is not completely settled, there are strong theoretical[4] arguments that this is the most feasible model. We are then naturally tempted to investigate whether this set of six leptons and six quarks (the latter in three color states each) is the ultimate set of fundamental fermionic components of matter.

The interest in this problem has recently led (see Refs. 5 and 6 for earlier references) to proposals of many models for a more fundamental structure. We are, however, very far from a definite answer, mainly due to the fact that a structure of quarks and leptons would involve phenomena at distances of the order of 10^{-16} cm or smaller, which are not experimentally accessible at present.

An important step along this direction would be the experimental discovery of a fundamental fermion with spin $\frac{3}{2}$. This might then give indications on whether the currently known families are really fundamental or not; on whether both quarks and leptons are fundamental or if they are on a different level[7]; on whether the families are to be simply repeated or whether we should consider each one as composed of spin $\frac{1}{2}$ and spin $\frac{3}{2}$ fermions.

We have previously presented a discussion of these possibilities[5] for the leptonic sector and investigated in a phenomenological and model-independent way some of the experimental consequences of such a hypothesis. In this paper we turn our attention to the quark sector.

A first possibility is to consider that spin-$\frac{3}{2}$ quarks would appear in an independent and sequential family: $(u,d)_{1/2}$, $(c,s)_{1/2}$, $(t,b)_{1/2}$, $(q_1,q_2)_{3/2}$, etc. Another scheme is to assume that in each family there may exist a corresponding spin-$\frac{3}{2}$ state, as in Table I.

Of course, we must decide between these alternatives by comparing them with experiment. This is particularly difficult, since even for electromagnetic interactions there is no completely renormalizable theory for spin-$\frac{3}{2}$ interacting fields. A phenomenological weak current for spin-$\frac{3}{2}$ fermions would lead to similar difficulties. Within the usual Rarita-Schwinger formalism, the simplest $V \pm A$ currents for a spin-$\frac{1}{2} \to$ spin-$\frac{3}{2}$ transition would be

$$j_1^{\alpha} = \bar{u}^{\alpha}(p, s=\tfrac{3}{2})(1+a\gamma^5)u(p', s=\tfrac{1}{2}) \tag{1}$$

and

$$j_2^{\alpha} = \frac{1}{M}\bar{u}^{\lambda}(p, s=\tfrac{3}{2})q_{\lambda}\gamma^{\alpha}(1+a\gamma^5)u(p', s=\tfrac{1}{2}), \tag{2}$$

where u^{α} is a Rarita-Schwinger vector spinor, a is equal to ± 1, and $q = p - p'$. There exist more general forms, but they present the same difficulties as in the electromagnetic case. In order to have a phenomenological estimate for the physical processes, we shall be mainly interested in the least divergent forms (1) and (2). Our guess is that a complete formalism that provides a self-consistent theory will present this behavior at some level, in the same sense that the old four-fermion interaction is a good approximation to the more satisfactory gauge theories.

The currents j_1 and j_2 imply a departure from the usual scaling behavior of spin-$\frac{1}{2}$ partons. If we consider the weak transition spin $\frac{1}{2} \to$ spin $\frac{3}{2}$ in

TABLE I. Possible correspondence between spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ quarks.

Spin $\frac{1}{2}$	Spin $\frac{3}{2}$
u	$\mathfrak{U}$
d	$\mathfrak{D}$
c	$\mathfrak{C}$
s	$\mathfrak{S}$
b	$\mathfrak{B}$
t	$\mathcal{T}$

neutrino-nucleon scattering as in Fig. 1, the hadronic tensor corresponding to an interaction with the current (2) will be

$$W_{\alpha\beta}(\tfrac{1}{2}\to\tfrac{3}{2})=\frac{16}{3}\frac{(p_i\cdot p_f)^2}{M^4}\,[p_i^\alpha p_f^\beta+p_i^\beta p_f^\alpha-g^{\alpha\beta}(p_i\cdot p_f)+i\epsilon_{\beta\alpha ab}p_f^a p_i^b]\,. \quad (3)$$

Using the standard techniques of the parton model[8] we find for the structure functions in the Bjorken limit

$$F_i'(x,Q^2,\tfrac{3}{2})=\frac{1}{6}\frac{Q^4}{M^4}F_i(x,\tfrac{1}{2}),\quad i=1,2,3 \quad (4)$$

where M is the spin-$\frac{3}{2}$ mass and $F_i(x,\frac{1}{2})$ are the usual spin-$\frac{1}{2}$ structure functions. The $F_i'(x,Q^2,\frac{3}{2})$ are related by equations of the same Callan-Gross type for spin $\frac{1}{2}$ but present a very definite scaling violation: There is a linear rise with Q^4 which is different from what is expected by gauge theories as quantum chromodynamics.[9] Of course, this behavior cannot be true for all energies since unitarity will be violated, but as claimed above, we expect that it will appear at least at lower energies in the production of spin-$\frac{3}{2}$ partons. We remark that a similar result was obtained by Taylor[10] for electron deep-inelastic scattering.

The corresponding cross sections for neutrino- and antineutrino-nucleon scattering are

$$\frac{d^2\sigma^{\nu,\bar\nu}}{dx\,dy}=\frac{G^2ME}{\pi}\frac{1}{6}\frac{Q^4}{M^4}[xy^2F_1+(1-y)F_2\pm(1-y/2)xyF_3]\,, \quad (5)$$

where F_i are the spin-$\frac{1}{2}$ structure functions.

For the other interaction equation (1) we still obtain scaling violations but in a rather different form. The spin-$\frac{1}{2}$ Callan-Gross relations are no longer respected. Instead of them, we obtain (for neutrinos)

$$F_1(x)=F_3(x)\,,\qquad F_2(x,Q^2)=\frac{xQ^2}{2M^2}F_1(x)\,. \quad (6)$$

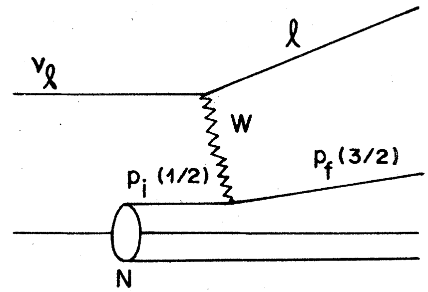

FIG. 1. Lowest-order diagram for a spin-$\frac{3}{2}$-quark excitation in neutrino-nucleon reactions.

We can compare these structure functions with the spin-$\frac{1}{2}$ structure functions:

$$F_1(x,\tfrac{3}{2})=\tfrac{2}{3}F_1(x,\tfrac{1}{2})\,,\qquad F_2(x,Q^2,\tfrac{3}{2})=\frac{Q^2}{6M^2}F_2(x,\tfrac{1}{2})\,,\qquad F_3(x,\tfrac{3}{2})=\tfrac{2}{3}F_3(x,\tfrac{1}{2})\,. \quad (7)$$

Besides the scaling violations in a pattern defined by Eqs. (7) we remark that the most significant departure from spin-$\frac{1}{2}$ quarks will be the Q^2 *dependence of the y distributions*. This can be seen from the expressions for the cross sections

$$\frac{d^2\sigma^{\nu,\bar\nu}}{dxdy}=\frac{G^2ME}{\pi}\left[xy^2\tfrac{2}{3}F_1(x,\tfrac{1}{2})+(1-y)\frac{Q^2}{6M^2}F_2(x,\tfrac{1}{2})\pm(1-y)xy\tfrac{2}{3}F_3(x,\tfrac{1}{2})\right]. \quad (8)$$

With the above cross section, Eqs. (5) and (8), we can easily identify the production of spin-$\frac{3}{2}$ quarks in neutrino-nucleon scattering. These objects should also be recognized through their decay properties. The calculations we presented in Ref. 5 for leptons can be easily applied here, as well as in the production of a pair of spin-$\frac{3}{2}$ quarks in e^+e^- collisions.

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