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SPIN 3/2 FERMIONS: A WINDOW TO NEW PHYSICS?

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ABSTRACT

We present a systematic study of production and decay properties of hypothetical spin 3/2 fermions. These objects could indicate a structure for the presently known matter.

Key-words: Composite leptons; Production; Decay.

1 - INTRODUCTION

From the early days of greek philosophers up to the latest results in modern elementary particle physics, the quest for the ultimate nature of matter has been one of the most fascinating activities of human knowledge. For example, in the last century the periodic table of elements was settled as one of the most remarkable models for understanding a large number of properties from a very simple structure of atomic nuclei and a reduced number of subcomponents. More recently the enormous number of hadronic states was understood as the result of a relatively simple interaction - quantum chromodynamics - among a few elementary subcomponents - the quarks. These quarks and their even more simpler companions - the leptons, are presently the ultimate building blocks of matter. These objects can interact through the exchange of vector bosons - the photon, the heavy weak-interacting $W^{\pm}$, Z^0 and the coloured gluons beside the graviton.

Only very recently [1] the new LEP results on electron-positron production and decay of the Z^0 has fixed the number of fermionic families to be equal to three. According to the present view we have the following elementary objects: six leptons; six quarks, each one in three coloured states; the photon; the weak vector bosons $W^{\pm}$ and Z^0 and the eight coloured gluons. All fermionic masses and coupling parameters are fixed from experiment.

Even if this scheme, known today as the standard model, has no disagreement with experiment, the large number of elements naturally raises the question: is this the ultimate structure of matter? Up to distances so small as 10^{-17}cm the answer is yes. We have a point - like behaviour of objects with quantum mechanical fields associated to them. But their large number and the repetition of properties in each family has motivated a large number of extensions of the standard model in the hope of finding again a simpler structure of matter and their interactions. No model has succeeded so far and this happens for a simple reason: no experimental fact seems to indicate a physical window to the "new physics".

In a series[2,7] of papers we have stressed the point that the first step towards an understanding of the hypothesis of compositeness is to be found in the experimental discovery of excited states for the presently known matter. If quarks and leptons are bound states of three fundamental fermions (spin 1/2) and the vector bosons are composite states of two of them, we must have excited fermions with spin 3/2 and new interacting bosons with spin 0.

In this paper we review the status of spin 3/2 field theory and present phenomenological estimates for their experimental finding.

2 - SPIN 3/2 FIELDS

The usual description of spin 3/2 fields is given by the Rarita - Schwinger vector - spinor $\psi_\mu^a(x)$ where $a=1,2,3,4$ is a spinor index and $\mu=0,1,2,3$ a Lorentz index. The equation of motion are

$$(i\gamma_\mu \partial^\mu - m)\psi_\nu^a(x) = 0 \qquad (1)$$

With the constraints

$$\partial_\mu \psi_a^\mu(x) = 0 \qquad (2)$$

$$\gamma_\mu \psi_a^\mu(x) = 0$$

we recover the correct number of degrees of freedom for a spin -3/2 field.

It can be shown[3] that there exists a unique lagrangian

$$\mathcal{L}_{RS} = -\bar{\psi}_\alpha \varepsilon^{\alpha\mu\nu\beta} \gamma^5 \gamma_\mu (\partial_\nu + i\frac{M}{2}\gamma_\nu)\psi_\beta \qquad (3)$$

with the following equation of motion

$$\varepsilon^{\alpha\mu\nu\beta} \gamma^5 \gamma_\mu (\alpha_\nu + i\frac{M}{2}\gamma_\nu)\psi_\beta = 0 \qquad (4)$$

which is equivalent to the system of equations (1) and (2).

If we normalize the vector - spinors by

$$\bar{u}^\alpha(p,s) u_\alpha(p,s) = -1 \qquad (5)$$

$$\bar{v}^\alpha(p,s) v_\alpha(p,s) = +1$$

then the projectors are given by

$$P^{(+)\mu\nu}(p) = \sum_s u^\mu(p,s)\bar{u}^\nu(p,s) = \frac{(\not{p}-m)}{2m}\left(g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{\not{p}^\nu\not{p}\gamma^\mu}{3m^2} - \frac{\not{p}^\mu\gamma^\nu\not{p}}{3m^2}\right) \tag{6}$$

and

$$P^{(-)\mu\nu}(p) = \sum_s v^\mu(p,s)\bar{v}^\nu(p,s) = -P^{(+)\mu\nu}(-p)$$

The massless case $m_{3/2} = 0$ has an interesting connection with the spinor-gauge invariant transformation

$$\psi^\mu_a(x) \to \psi^\mu_a(x) + \partial^\mu\phi_a(x) \tag{7}$$

where $\phi(x)$ is an arbitrary spinor.

3 - INTERACTING FIELDS

We are taking as a starting point the hypothesis that to each known fermion with spin 1/2 there is a corresponding excited state with spin 3/2. This means that there must exist transitions of the type spin 3/2 $\rightleftarrows$ spin 1/2 mediated by some interaction. Unfortunately even in the simplest case of electromagnetic interactions for the Rarita - Schwinger fields we lack a completely renormalizable theory.

In order to have phenomenological estimates for physical processes we can use V ± A currents of the type

$$J^\alpha_1 = \bar{u}^\alpha(3/2)(1 + a\gamma^5)\mu(1/2) \tag{8}$$

$$J_2^{\alpha} = \frac{1}{M}\,\bar{u}^{\lambda}(3/2)\,q_{\lambda}\gamma^{\alpha}(1 + b\gamma^5)\,u(1/2) \tag{9}$$

normalized in terms of the Fermi constant $G_F/\sqrt{2}$. Our guess is that a complete formalism that provides a self - consistent theory will present this behaviour in the same sense that the old four - fermion interaction is a good approximation to the more satisfactory gauge theories.

It is also possible to develop an heuristic $SU_L(2) \times U_Y(1)$ model for spin 3/2 fields [4]. If we define left - handed Rarita-Schwinger doublets and right - handed singlets we have the following generalization of the free - field lagrangian

$$\mathcal{L} = -\,\varepsilon^{\mu\nu\rho\sigma}\bar{L}_{\mu}\gamma_5\gamma_{\nu}D_{\rho}L_{\sigma} - \varepsilon^{\mu\nu\rho\sigma}\bar{R}_{\mu}\gamma_5\gamma_{\nu}D_{\rho}R_{\sigma} \tag{10}$$

where derivatives are given as in the standard model notation. This model allows the incorporation of charged and neutral current interactions with the same characteristics of the standard model. Spin 3/2 $\leftrightarrow$ spin 1/2 transitions can also be obtained generalizing the free - field lagrangian to

$$\mathcal{L} = -\,\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_{\mu}\gamma_5\gamma_{\nu}D_{\rho}D_{\sigma}\psi \tag{11}$$

4 - PRODUCTION AND DECAYS OF SPIN 3/2 FERMIONS

In the simplest case of minimal electromagnetic interaction given by the current

$$J^{\mu} = \bar{\psi}^{\alpha}\gamma^{\mu}\psi_{\alpha} \tag{12}$$

the cross section of the process $e^+e^- \to L^+_{3/2}L^-_{3/2}$ is given by [2]

$$\frac{\sigma(e^+e^- \to L^+_{3/2}L^-_{3/2})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{|\vec{P}|}{E}\left(\frac{16}{9}\gamma^4 - \frac{8}{9}\gamma^2 - \frac{2}{9} + \gamma^{-2}\right) \tag{13}$$

where $\vec{P}$ and E are the momentum and energy of the spin 3/2 heavy leptons in the center of mass system and $\gamma = E/M$. This expression violates unitary just above the energy threshold.

The phenomenological currents given by equations (8) and (9) allow a single spin 3/2 production through the process $e^+e^- \to Z^* \to L^+_{3/2}e^-_{1/2}$. If we consider the same neutral couplings of the standard model, then near the Z_0 pole we have the following cross sections for this process

$$\sigma_1 = \frac{G_F^2 M^2_{3/2}}{27\pi\sin^2\theta_w} \frac{\left[1 + (1-4\sin^2\theta_n)^2\right]^2}{(s/M_z^2 - 1)^2 + \Gamma_z^2/M_z^2} \tag{14}$$

$$\cdot\{8\gamma^4 + 18\gamma^2 - 9 + 1/\gamma^2 + 1/32\gamma^4\}$$

and

$$\sigma_2 = \frac{G_F^2 M^2_{3/2}}{27\pi\sin^2\theta_w} \frac{\left[1 + (1-4\sin^2\theta_w)^2\right]^2}{(s/M_z^2 - 1)^2 + \Gamma_z^2/M_z^2} \tag{15}$$

$$\cdot\{64\gamma^6 - 56\gamma^4 + 16\gamma^2 - 1 - 1/4\gamma^2 + 1/32\gamma^4\}$$

A detailed analysis of the process $pp \to L_{3/2}\ell_{1/2}\, x$ was given by Spehler et al.[5].

We can have the production of new quarks with spin 3/2 in the usual neutrino-nucleon deep-inelastic scattering[6]. For the current j_2^α we obtain

$$\frac{d^2\sigma^{\nu,\bar{\nu}}_{(2)}}{d\,xdy} = \frac{G_F^2 ME}{\pi}\,\frac{Q^4}{6M^4_{3/2}}\left[xy^2F_1 \pm (1-y)F_2 \pm (1-y/2)xyF_3\right]$$

where F_i are the spin 1/2 structure functions. We see clearly a departure from the usual scaling violations. For the other current J_1^α we obtain

$$\frac{d^2\sigma^{\nu,\bar{\nu}}_{(1)}}{d\,xdy} = \frac{G_F^2 ME}{\pi}\left[xy^2\,\frac{2}{3}F_1 + (1-y)\frac{Q^2}{6M^2_{3/2}}\,F_2 \pm (1-y)xy\,\frac{2}{3}F_3\right]$$

In this case the most significant departure from spin 1/2 quarks will be the Q^2 dependence of the y distributions.

Let us now turn our attention to the decay possibilities of spin 3/2 leptons. Through charged current couplings we have decays such as

$$L^-_{3/2} \to \pi^- + (\nu_\ell)_{L,R}$$

$$L^-_{3/2} \to (\nu_\ell)_{L,R} + \ell^- + \bar{\nu}_\ell$$

and through neutral currents

$$L^-_{3/2} \to e^- + e^- + e^+$$

$$L^-_{3/2} \to e^- + \mu^- + \mu^+$$

Decay amplitudes and energy spectrum for several interactions were given in references 2 and 7 and will not be reproduced here.

5 - CONCLUSIONS

In this paper we have stressed the possibility of new spin 3/2 leptons and quarks as excited states of the presently known fermions. In a rather different context, supersymmetric theories include supermultiplets with spin 3/2. In supergravity models a fundamental role is given to the gravitino - a spin 3/2 particle.

Although we lack a complete formalism for spin 3/2 interacting fields we can establish phenomenological interactions of a general type and suggest experimental tests to verify the behaviour of these objects.

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