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Limits on excited spin-$\frac{3}{2}$ leptons

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The constraint on the electromagnetic decay widths of excited spin-$\frac{3}{2}$ leptons by electron and muon anomalous magnetic moments is computed. Also shown are the invariant-mass distributions for Z decay via a spin-$\frac{3}{2}$ excited lepton.

The UA1 and UA2 Collaborations at CERN have recently made some exciting discoveries. Among these are the anomalous $Z^0 \to \mu^+\mu^-\gamma$ and $e^+e^-\gamma$ events,[1] the single-jet events,[2] and a possible bump in the multijet mass distribution[3] at 147 ± 5 GeV with a width of 11 ± 5 GeV. Several authors have proposed the existence of excited leptons and quarks.[4] If ultimately confirmed, the excited quarks and leptons would naturally point towards identifying quarks and leptons as composite objects of more fundamental entities.

In the conjectured scenario of an excited lepton, there seems at present a theoretical bias in assuming that they are spin-$\frac{1}{2}$ objects like e^- or μ^-. This stems from the recent observation of Weinberg and Witten[5] who show that *massless* particles with spin $> \frac{1}{2}$ are forbidden as composite objects in all renormalizable quantum field theories. Also 't Hooft[6] has argued that unitarity and locality forbid the occurrence of massless fermionic bound states with spin $> \frac{1}{2}$. It is not immediately obvious that particles of masses in the range 50–60 GeV can be treated as massless chiral composites. They may as well be intrinsically heavy composites (as considered, e.g., by Baur and Fritzsch[7]) for which higher-spin possibilities are not ruled out. As a matter of fact composite models leading to Regge trajectories (and consequently higher-spin possibilities) have been considered by Schnitzer[8] and by Kovesi-Domokos and Domokos;[9] these authors very interestingly also show that if hypercolor and hyperflavor satisfy certain conditions, then relatively light excited particles (~ 60 GeV) can exist in nature.[9]

Once we accept the possibility that the hypothetical excited lepton is a spin-$\frac{3}{2}$ object, it is interesting to work out the restrictions imposed on such an object by the very remarkable agreement between theory and experiment of value of $(g-2)$ for the muon and electron. This is what we attempt in this Rapid Communication. A recent analogous work for spin-$\frac{1}{2}$ composites by Renard[10] finds the restriction imposed by $(g-2)$ measurement on the coupling constants of the composite object.

For the interaction of a spin-$\frac{3}{2}$ l^* with a lepton l and photon field $F_{\mu\nu}$ we take the gauge-invariant form[11]

$$L_I = -\frac{e\lambda}{M}\bar{\psi}\gamma_\rho\gamma_5\psi_\mu F_{\mu\rho} + \text{H.c.} \ , \tag{1a}$$

which yields the vertex factor

$$\Gamma_{\mu\rho} = -\frac{ie\lambda}{M}(q\gamma\delta_{\mu\bar{\rho}}q\gamma_\rho)\gamma_\mu\gamma_5 \tag{1b}$$

for Fig. 1(a) where M is the excited-lepton mass and λ the coupling constant. The excited lepton is described by a spin-$\frac{3}{2}$ Rarita-Schwinger field ψ_μ. Using (1), we now consider the contribution of the diagram [Fig. 1(b)] to the magnetic moment of the lepton. Unlike QED, the interaction (1) is not a renormalizable one. One is forced to use a cutoff Λ_h whose magnitude should reflect the size of the composite quarks and leptons and is in the range of 1 TeV. With the understanding that all divergencies will be controlled with a cutoff, the contribution of Fig. 1(b) is

$$M_\mu(p,q) = -e\left(\frac{e\lambda}{M}\right)^2 \int \frac{d^4k}{2\pi)^4} k_{\alpha_1}k_{\alpha_2}\frac{-i\delta_{\beta_1\beta_2}}{k^2-i\epsilon}\gamma_{\sigma_1}\gamma_5 S_{F\rho_1\phi}(p_1+q-k)$$
$$\times(\delta_{\alpha_1\sigma_1}\delta_{\beta_1\rho_1}-\delta_{\alpha_1\rho_1}\delta_{\beta_1\sigma_1})\gamma_\mu S_{F\phi\rho_2}(p_1-k)\gamma_{\alpha_2}\gamma_5(\delta_{\alpha_2\sigma_2}\delta_{\beta_2\rho_2}-\delta_{\alpha_2\rho_2}\delta_{\beta_2\sigma_2}) \ . \tag{2}$$

In (2), $S_{F\mu\nu}$ is the spin-$\frac{3}{2}$ propagator[12]

$$S_{F\mu\nu}(k) = \frac{P_{\mu\nu}(k)}{k^2+M^2-i\epsilon} \ , \tag{3}$$

where $P_{\mu\nu}(k)$ is the covariant spin-$\frac{3}{2}$ projection operator

$$P_{\mu\nu}(k) = \left(\frac{\gamma\cdot k+iM}{2iM}\right) \times \left(\delta_{\mu\nu}-\tfrac{1}{2}\gamma_\mu\gamma_\nu+\frac{i}{3M}(\gamma_\mu k_\nu-\gamma_\nu k_\mu)+\frac{2}{3M^2}k_\mu k_\nu\right) \ . \tag{4}$$

In writing the Rarita-Schwinger propagator, we have re-

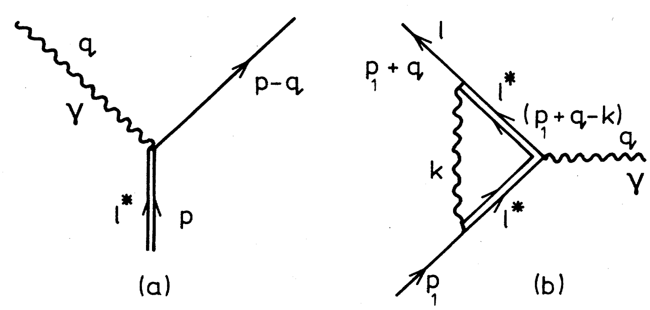

FIG. 1. (a) The decay $l^* \to l+\gamma$. (b) The graph through which l^* contributes to $(g-2)$ of the lepton (l).

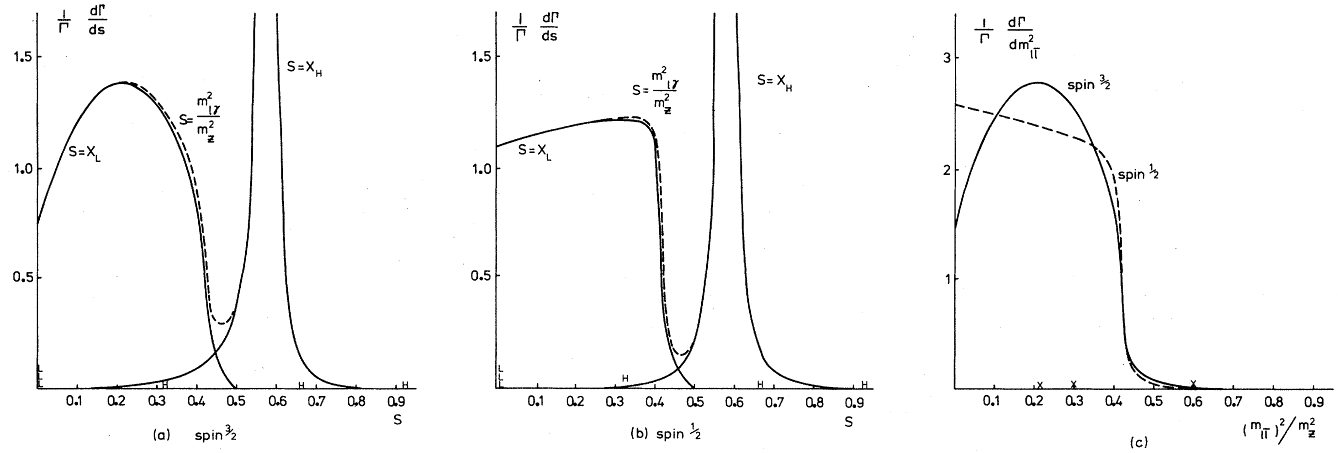

FIG. 2. (a) The invariant-mass distributions, for $M_{l\gamma}{}^2$, X_H, and X_L, for Z decay via a spin-$\frac{3}{2}$ excited lepton of mass 70 GeV. The CERN events are shown on the axis. (b) The invariant-mass distributions, for $M_{l\gamma}{}^2$, X_H, and X_L for Z decay via a spin-$\frac{1}{2}$ excited lepton of mass 70 GeV. The CERN events are shown on the axis: H = high, L = low events. (c) The invariant-mass distributions for $M_{l\bar{l}}$ for decay via spin-$\frac{3}{2}$ and spin-$\frac{1}{2}$ excited leptons.

tained only the resonating part representing the effect of a genuine high-spin propagation. The expression (2) can be evaluated and in the leading order of the cutoff gives

$$M_\mu \simeq \frac{e}{2m}\left(\frac{\alpha}{2\pi}\right)\sigma_{\mu\nu}q_\nu\left(\frac{m\Lambda_h{}^4}{M^5}\frac{\lambda^2}{9}\right) , \tag{5}$$

where m is the lepton mass. Using the experimental limits[13] of non-QED contributions to $(g-2)$ of the electron[14] and muon[15] and taking $\Lambda_h \sim 1$ TeV, $M \sim 70$ GeV yields the following limits on the electron and muon coupling constants λ_e and λ_μ:

$$\lambda_e{}^2 \lesssim 10^{-5}, \quad \lambda_\mu{}^2 \lesssim 10^{-6} . \tag{6}$$

These numbers are at least three orders of magnitude less than the corresponding dimensionless coupling constant quoted by Renard[10] and this comes about because of the very bad high-energy behavior of a spin-$\frac{3}{2}$ particle. In terms of the decay width of the excited lepton [Fig. 1(b)],

$$\Gamma_{l^*\to l\gamma} \simeq \frac{\alpha}{4}|\lambda|^2\left(M - \frac{4m^3}{M^2} - \frac{2m^2}{M}\right) , \tag{7}$$

the constraints of Eq. (6) imply widths

$$\Gamma_{e^*\to e\gamma} \lesssim 1 \text{ keV}, \quad \Gamma_{\mu^*\to \mu\gamma} \lesssim 0.1 \text{ keV} .$$

With a little more statistics the width of the excited lepton, if it exists, would be easy to determine. Should the spin be actually $\frac{3}{2}$, our result would suggest that this massive particle exists with the tiniest of electromagnetic widths.

Better statistics will also provide the invariant-mass distribution for the postulated decay $Z \to l^*\bar{l} + \bar{l}l^* \to l\bar{l}\gamma$. In Fig. 2 we give the distributions for decay via an excited spin-$\frac{3}{2}$ lepton and via an excited spin-$\frac{1}{2}$ lepton for comparison. The mass of the excited lepton is again taken to by 70 GeV with total width 1 GeV. Also shown are the high (X_H) and low (X_L), invariant-mass distributions which should be used when the $l\gamma$ and $\bar{l}\gamma$ pairs are not differentiated. The high and low invariant-mass parameters are given by

$$X_H = \max\left\{\frac{(M_{l\gamma})^2}{M_Z{}^2}, \frac{(M_{\bar{l}\gamma})^2}{M_Z{}^2}\right\} ,$$

$$X_L = \min\left\{\frac{(M_{l\gamma})^2}{M_Z{}^2}, \frac{(M_{\bar{l}\gamma})^2}{M_Z{}^2}\right\} ,$$

where $M_{l\gamma}, M_{\bar{l}\gamma}$ are the lepton-photon invariant masses and $M_{l\bar{l}}$ is the lepton-pair invariant mass.

In conclusion, the $(g-2)$ experiments provide a strong constraint on the spin-$\frac{3}{2}$ $l^*l\gamma$ coupling. The mass distributions may help to differentiate between the possibilities of a spin-$\frac{3}{2}$ or spin-$\frac{1}{2}$ excited lepton, or other possible explanations[16] of the CERN $l\bar{l}\gamma$ events; however, any firm conclusion must await better statistics.

Note added. There are also contributions to the lepton magnetic moment to the same order in λ from a spin-$\frac{3}{2}$ and an ordinary lepton in the triangle diagram; however, these are suppressed by $O(\Lambda_h{}^2/M^2)$ relative to Fig. 1(b) and can be safely neglected.

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