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Тяжелые лептоны в суперсимметричной модели слабых и электромагнитных взаимодействий

Обсуждаются распады тяжелых лептонов в суперсимметричной модели слабых и электромагнитных взаимодействий и их рождение в $p\bar{p}$ - столкновениях.

Работа выполнена в Лаборатории теоретической физики

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Decay Properties of Heavy Leptons in the Supersymmetric Model of Weak and E.M. Interactions

Decay properties of heavy leptons in the SU(2)xSU(2)xU(1) supersymmetric model of weak and electomagnetic interactions are studied. The partial and total decay rates and the production in $p\bar{p}$ collision of one of them are estimated for various values of its mass.

The Investigation has been performed at he Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1979

1. Introduction

It is shown in the article/1/ that unified lepton models may be formulated in a supersymmetric way. The most realistic is the SU(2)xSU(2)xU(1) supersymmetric model. In paper/2/ quarks, also, are included in the model in a supersymmetric way, and it is shown that neutral current predictions of our model coincide (to within 1%) with predictions of the Weinberg-Salam (W.-S.) theory, in agreement with experimental data. The main differences between our supersymmetric model and standard W.-S. model concern heavier leptonic sector. Five charged heavy leptons E_i are predicted. One of them E_1 can be identified with τ (1,8 GeV) lepton. The masses of E_2 and E_3 satisfy the sum rule

$$m_2^2 + m_3^2 = 2M_W^2 \tag{1.1}$$

and thus

$$m_\tau < m_2 < M_W$$

$$M_W < m_3 < \sqrt{2}\, M_W$$

Here M_W is the mass of the light intermediate vector meson. E_4 lepton has the mass

$$m_4 \approx \sqrt{2}\, M_{W'}$$

where $M_{W'}$ is the mass of the heavy intermediate vector meson $W'(M_{W'} \gg M_W)$. The mass of E_5 is, also, of the order of $M_{W'}$ and, therefore, they both are not discussed here.

The decay mode $E_3 \to W + \nu$ is proportional to the Fermy coupling G rather than G^2 and will completely dominate other weak decay widths, which are proportional to G^2.

The decay channels of E_2 are richer, and they are estimated as functions of the mass of E_2.

II. Heavy Leptons and Charged Current

The charged current interacting with the lighter intermediate vector meson W is[1,2]

$$j^\lambda = \bar{\nu}_e \gamma^\lambda (1-i\gamma^5) e + \bar{\nu}_\mu \gamma^\lambda (1-i\gamma^5)\mu + \bar{\nu}\gamma^\lambda(1-i\gamma^5)E_1 + 2^{1/2}\sin\theta\,\bar{\nu}_0\gamma^\lambda(1-i\gamma^5)E_2 +$$

$$+ 2^{-1/2}\frac{m_3}{M_W}\bar{\nu}_1^c\gamma^\lambda(1+i\gamma^5)E_2 + 2^{-1/2}\frac{m_2}{M_W}\bar{\nu}_1\gamma^\lambda(1-i\gamma^5)E_3 - 2^{1/2}\sin\theta\,\bar{\nu}_0^c\gamma^\lambda(1+i\gamma^5)E_3 \qquad (2.1)$$

θ is Weinberg's angle ($\sin^2\theta \approx 0.25$).

The masses of W, E_1, E_2, E_3 are determined by the formulas

$$M_W^2 = \frac{g_2^2}{2}(\alpha_+^2 + \alpha_-^2) \qquad (2.2)$$

$$m_1 = |g_1\alpha_+|\,, \quad m_2 = |g_2\alpha_+|$$

$$m_2^2 + m_3^2 = 2M_W^2$$

with $g_2 = e/\sin\theta$. Here g_1, g_2 are gauge couplings, α_+, α_- arbitrary parameters with dimension of mass. There are three free parameters g_1, α_+, α_-, and we can give arbitrary mass to W, E_1, E_2. Thus our theory predicts only the sum rule (1.1) for masses m_2, m_3, M_W and the form of interactions with intermediate vector mesons (charged and neutral).

Identifying E_1 with τ lepton ($m_1 = m_\tau = 1{,}8$ GeV) one obtains good agreement with experimental data[3].

III. Leptonic Decays of E_2

Leptinic decay channels of E_2 can be divided into two groups

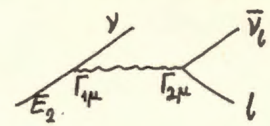
1. with neutrino ν_0

$$E_2 \to e\bar{\nu}_e\nu_0\,,\ \mu\bar{\nu}_\mu\nu_0\,,\ \tau\bar{\nu}_\tau\nu_0$$

2. with neutrino ν_1

$$E_2 \to e\bar{\nu}_e\bar{\nu}_1\,,\ \mu\bar{\nu}_\mu\bar{\nu}_1\,,\ \tau\bar{\nu}_\tau\bar{\nu}_1$$

The widths of these decays are determined by the diagram



where

$$\Gamma_{1\mu} = \begin{cases} \bar{\nu}_0\gamma_\mu(1-i\gamma^5)E_2\,, & \text{for group 1.} \\ \bar{\nu}_1^c\gamma_\mu(1+i\gamma^5)E_2\,, & \text{for group 2.} \end{cases}$$

$$\Gamma_{2\mu} = \bar{\nu}_l\gamma_\mu(1-i\gamma_5)l$$

l denotes e, μ or τ.

The answer is

$$\Gamma(E_2 \to l\bar{\nu}_l\nu_0) = 2\sin^2\theta\,\Gamma_- \qquad (3.1)$$

$$\Gamma(E_2 \to l\bar{\nu}_l\bar{\nu}_1) = \frac{m_3^2}{2M_W^2}\Gamma_+ \qquad (3.2)$$

$$\Gamma_- = \Gamma_0 m_2^5\Big[\frac{12}{x^3} - \frac{6}{x^2} - \frac{2}{x} - \frac{12y}{x^4} + \frac{6y}{x^2} - \frac{6y}{x} + \frac{6y^2}{x^4} - \frac{6y^2}{x^3} +$$

$$+ \frac{12y^2}{x} + \frac{2y^3}{x^4} + \frac{6y^3}{x^3} - \frac{12y^3}{x^2} - 12(1-y)\Big(\frac{1}{x^4} - \frac{1}{x^3} + \frac{2y}{x} - \frac{3y^2}{x^2} + \qquad (3.3)$$

$$+ \frac{y^2}{x}\Big)\ln\frac{1-y}{1-x} + \frac{12y^2}{x^2}(1-x)(1-y)\ln\frac{x}{y}\Big]$$

$$\Gamma_+ = \Gamma_0 m_2^5 \Big[\frac{12}{x^3} - \frac{6}{x^2} - \frac{2}{x} - \frac{12y}{x^4} + \frac{6y}{x^2} - \frac{6y}{x} + \frac{6y^2}{x^4} - \frac{6y^2}{x^3} + \frac{12y^2}{x} +$$
$$+ \frac{2y^3}{x^4} + \frac{6y^3}{x^3} - \frac{12y^3}{x^2} + 12\Big((1-y)\Big(\frac{1}{x^4} - \frac{1}{x^3}\Big) - \frac{y^2}{x^2} + \frac{y^3}{x^2} - \frac{y^3}{x} + \frac{y^4}{x^3}\Big) \cdot$$
$$\cdot \ln\frac{1-x}{1-y} + 12\Big(-\frac{1}{x^2} - \frac{y}{x} + \frac{y}{x^2} + \frac{y^2}{x^3}\Big) y^2 \ln\frac{x}{y} \Big] \tag{3.4}$$

where

$$\Gamma_0 = \frac{G^2 (GeV)^5}{192\pi^3} = 3.47 \times 10^{10}\ \mathrm{sec}^{-1}, \quad x = \frac{m_2^2}{M_W^2}, \quad y = \frac{m_\ell^2}{M_W^2}$$

and m_2 is in GeV.

For $m_2 \gtrsim 10$ GeV and $M_W = 74$ GeV the corrections due to masses of e, μ, τ are negligible (for $\tau \lesssim 1\%$) and setting $m_\ell = 0$ one obtains $\Gamma_- = \Gamma_+ \equiv \Gamma$

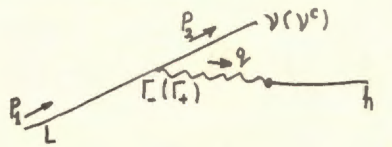
$$\Gamma = \Gamma_0 m_2^5 \Big[\frac{12}{x^3} - \frac{6}{x^2} - \frac{2}{x} + 12\Big(\frac{1}{x^4} - \frac{1}{x^3}\Big) \ln(1-x) \Big] \tag{3.5}$$

Note that a "normal" lepton N of the mass m_2 with $V-A$ current $\bar{\nu}\gamma^\lambda(1-i\gamma^5)N$ and with $e\mu N$ universality would have a leptonic decay width equal to Γ :

$$\Gamma(N \to \ell \bar{\nu}_\ell \nu) = \Gamma \tag{3.6}$$

IV. Semihadronic Decays

Consider a decay of the type $L \to \nu(\nu^c) + h$



Here $\Gamma_- = \bar{\nu}\gamma^\mu(1-i\gamma^5)L$, $\Gamma_+ = \bar{\nu}^c\gamma^\mu(1+i\gamma^5)L$, L is a heavy lepton, h can be $\pi, \rho, K, \ldots$. It is easy to verify that the width of this process is irrelative to the sign of γ^5 in $\Gamma_\pm$. Indeed

$$|M|^2 \sim Sp[\hat{p}_2\gamma^\mu(1 \pm i\gamma^5)(\hat{p}_1 + M)\gamma^\nu(1 \pm i\gamma^5)]\, q_\mu q_\nu \sim$$
$$\sim Sp[(1 \pm i\gamma^5)\hat{p}_2\gamma^\mu\hat{p}_1\gamma^\nu]\, q_\mu q_\nu = Sp(\hat{p}_2\gamma^\mu\hat{p}_1\gamma^\nu)\, q_\mu q_\nu .$$

This means that the widths of $E_2 \to \nu_0 h, \bar{\nu}_1 h$ are associated with one of N ("normal") $\to \nu h$ as follows

$$\Gamma(E_2 \to \nu_0 h) = 2\sin^2\theta\, \Gamma(N \to \nu h).$$
$$\Gamma(E_2 \to \bar{\nu}_1 h) = \frac{m_2^2}{2M_W^2}\, \Gamma(N \to \nu h). \tag{4.1}$$

Let us list the known values of $\Gamma(N \to \nu h)$ /4/

$$\Gamma(N \to \nu\pi) = 6.4 \times 10^{10} M^3 (1 - M_\pi^2/M^2)^2 \ \mathrm{sec}^{-1}$$

$$\Gamma(N \to \nu K) = 0.46 \times 10^{10} M^3 (1 - M_K^2/M^2)^2 \ \mathrm{sec}^{-1}$$

$$\Gamma(N \to \rho\nu) = 18 \times 10^{10} M^3 (1 - M_\rho^2/M^2)^2 (1 + 2M_\rho^2/M^2) \ \mathrm{sec}^{-1}$$

$$\Gamma(N \to K^*\nu) = 1.29 \times 10^{10} M^3 (1 - M_{K^*}^2/M^2)^2 (1 + 2M_{K^*}^2/M^2) \ \mathrm{sec}^{-1}$$

$$\Gamma(N \to A_1\nu) = 35.2 \times 10^{10} M^3 (1 - M_{A_1}^2/M^2)^2 (1 + 2M_{A_1}^2/M^2) \ \mathrm{sec}^{-1} \tag{4.2}$$

$$\Gamma(N \to Q\nu) = 0.77 \times 10^{10} M^3 (1 - M_Q^2/M^2)^2 (1 + 2M_Q^2/M^2) \ \mathrm{sec}^{-1}$$

Everywhere in this section q^2 in the propogator of W meson is neglected because $q^2 \lesssim (1\ \mathrm{GeV})^2$.

Hadron Continuum

If $m_2 \gtrsim 10$ GeV one cannot neglect q^2 in the propogator of the intermediate vector meson. With due regard of this, one obtains

$$\Gamma(N \to \nu + \text{hadron cont.}) = \Gamma_0 M^5 \frac{2}{x^2}\Big[\frac{(4-3x)(1-y)}{x} + 1 - y^2 + \frac{6(1-x)}{x^2}\ln\frac{1-x}{1-yx} + \frac{(1-y)(2-3x+x^3)}{(1-x)(1-yx)x}\Big]\frac{F}{2}, \qquad (4.3)$$

where

$$x = \frac{M^2}{M_W^2}, \quad y = \frac{\Lambda^2}{M^2}, \quad \Lambda^2 \sim (1\,\text{GeV})^2,$$

F - number of flavors of relevant quarks. For $x \to 0$ this formula coincides with the one of /4/ and for $y \to 0$

$$\Gamma(N \to \nu + \text{had. cont.}) = F\,\Gamma/2,$$

where Γ is the function (3.5).

In conclusions J present the partial and total decay rates of E_2 for two values of m_2 (Table I).

V. $E_2^+E_2^-$-Pair Production in $p\bar{p}$ Collision

Here we discuss the Drell-Yan /5/ production mechanism of superheavy leptons. According to a common belief lepton pairs are produced by a quark-antiquark pair annihilation into l^+l^- through photon. Other quarks fragment into hadrons:

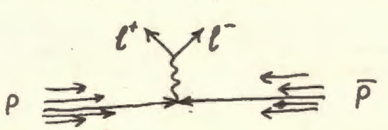


Table 1

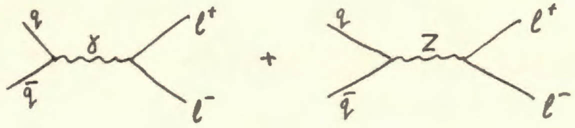
Predicted widths and branching ratios for E_2

	m_2 = 7,4 GeV		m_2 = 37 GeV	
Lifetime of E_2	1,6 x 10^{-16} sec		0,4 x 10^{-19} sec	
Lifetime of "normal"lepton N	1,5		11/8	
$\frac{\Gamma(E_2 \to \bar{\nu}_1 + X)}{\Gamma(E_2 \to \nu_0 + X)}$	2		7/4	
$\frac{\Gamma(E_2 \to \nu_0 + X)}{\Gamma(N \to \nu + X)}$	0.5		0.5	
decay mode of E_2	width in sec^{-1}	brenching ratios	width in sec^{-1}	branching ratios
$E_2 \to l\bar{\nu}_l\nu_0$	$3{,}85 \times 10^{14}$	6,3%	$28{,}4 \times 10^{17}$	6,1%
$\nu_0\pi$	$1{,}3 \times 10^{13}$	0,2%	$3{,}2 \times 10^{15}$	
$\nu_0 K$	$0{,}9 \times 10^{12}$	<0,1%	$2{,}3 \times 10^{14}$	
$\nu_0\rho$	$3{,}7 \times 10^{13}$	0,6%	$9{,}1 \times 10^{15}$	
$\nu_0 K^*$	$2{,}6 \times 10^{12}$	<0,1%	$6{,}5 \times 10^{14}$	
$\nu_0 A_1$	$0{,}7 \times 10^{14}$	1,1%	$1{,}8 \times 10^{16}$	
$\nu_0 Q$	$1{,}6 \times 10^{12}$	<0,1%	$3{,}9 \times 10^{14}$	
ν_0 + hadron continuum	$7{,}7 \times 10^{14}$	12,5%	$85{,}2 \times 10^{17}$	18,1%

X denote $(l,\bar{\nu}_l)$, π, K, ...
l is e, μ, τ

"normal" lepton N is a charged lepton with V-A current and with mass m_2.

But at very high dilepton masses the important process is the annihilation of quark-antiquark through intermadiate neutral vector boson Z. Thus the quark-antiquark annihilation into lepton pair is determined by two diagrams:



The cross section of this process is

$$\sigma = \frac{4\pi\alpha^2}{3Q^2}\Big\{\eta^2\Big(1+\frac{2m^2}{Q^2}\Big) - 2\eta\beta^2\frac{(a+b)(c+d)}{1-M^2/Q^2}\Big(1+\frac{2m^2}{Q^2}\Big) + \frac{\beta^4}{(1-M^2/Q^2)^2}\times$$
$$\cdot\times\Big(4(a^2+b^2)(c^2+d^2)\Big(1+\frac{2m^2}{Q^2}\Big)+24ab(c^2+d^2)\frac{m^2}{Q^2}\Big\}\Big(1-\frac{4m^2}{Q^2}\Big)^{1/2}, \qquad (5.1)$$

where η is the charge of the quarks; m, M, Q are the masses of lepton, Z -boson, and lepton pair, resp. Here we have assumed that the lepton and quark currents interacting with Z boson have the form:

$$j_l^Z = g(a\bar{l}\gamma^\mu(1-i\gamma^5)l + b\bar{l}\gamma^\mu(1+i\gamma^5)l)$$
$$j_q^Z = g(c\bar{q}\gamma^\mu(1-i\gamma^5)q + d\bar{q}\gamma^\mu(1+i\gamma^5)q) \qquad (5.2)$$

with $g=\beta e$ (l have unit charge e). For E_2 lepton

$$\beta = (2\sin\theta\cos\theta)^{-1}$$
$$a = \frac{1}{2}\cos^2\theta\ , \quad b = \Big(-\frac{1}{2}+\sin^2\theta\Big) \qquad (5.3)$$

The values c, d for quarks are as in the GIM model. Now the modified Drell-Yan cross section at zero rapidity for E_2 lepton pair looks as follows:

$$\frac{d\sigma}{dQ^2dy}\Big|_{y=0} = \frac{4\pi\alpha^2}{9Q^4}\tau\Big\{\Big[\frac{4}{9}\Big(1+\frac{2m^2}{Q^2}\Big)+0.04\Big(1+\frac{2m^2}{Q^2}\Big)\Big(1-\frac{M^2}{Q^2}\Big)^{-1}+$$
$$+\Big(0.20-0.15\frac{m^2}{Q^2}\Big)\Big(1-\frac{M^2}{Q^2}\Big)^{-2}\Big]\big(u(\sqrt{\tau})+s(\sqrt{\tau})\big)^2+\Big[\frac{1}{9}\Big(1+\frac{2m^2}{Q^2}\Big)-0.01\Big(1+\frac{2m^2}{Q^2}\Big)\times \qquad (5.4)$$
$$\times\Big(1-\frac{M^2}{Q^2}\Big)^{-1}+\Big(0.26-0.20\frac{m^2}{Q^2}\Big)\Big(1-\frac{M^2}{Q^2}\Big)^{-2}\Big]\Big(\big(d(\sqrt{\tau})+s(\sqrt{\tau})\big)^2+s^2(\sqrt{\tau})\Big)\Big\}\Big(1-\frac{4m^2}{Q^2}\Big)^{1/2}$$

where $\sqrt{\tau} = Q/\sqrt{S}$ and u, d, s are the parton-quark densities given by the formulas [6]

$$u(x) = \frac{1.79(1-x)^3(1+2.3x)}{\sqrt{x}}$$
$$d(x) = \frac{1.07(1-x)^{3.1}}{\sqrt{x}} \qquad (5.5)$$
$$s(x) = \frac{0.34(1-x)^9}{x}$$

I have estimated the value $s\frac{d\sigma}{d\sqrt{\tau}dy}\Big|_{y=0}$ for $\sqrt{S}/2 = 260$ GeV, $m_2 = 7.4$ and $m_2 = 37$ GeV at various values of Q . For the mass $m_2 = 7{,}4$ GeV. nonelectromagnetic terms in (5.4) are small. For $m_2 = 37$ GeV the terms proportional to $(1-M^2/Q^2)^{-2}$ are also important.

The function $s\,d\sigma/d\sqrt{\tau}dy$ for $m_2 = 7{,}4$ GeV, and $\frac{Q}{2} \lesssim 10$ GeV has maximum at $\frac{Q}{2} \simeq 8{,}6$ GeV.

$$\max s\frac{d\sigma}{d\sqrt{\tau}dy}\Big|_{y=0} \simeq 0.21\,\mu b$$

The same function for $\mu^+\mu^-$ -pair production at $\frac{Q}{2} \simeq 8.6$ GeV has the value

$$s\frac{d\sigma}{d\sqrt{\tau}dy}\Big|_{y=0}^{\mu^+\mu^-} \simeq 0.28\,\mu b$$

That is both of them are of the same order. This is true also for higher values of Q. Thus we conclude that $E_2^+E_2^-$ in $p\bar{p}$ collisions are produced as many as $\mu^+\mu^-$, $\tau^+\tau^-$ and the number of simultaneous μe events exceeds by about 70%-80% that one expected from τ decay.

For $m_2 = 37$ GeV. I have estimated the function $s\frac{d\sigma}{d\sqrt{\tau}dy}\Big|_{y=0}$ for Q in the interval

$$76 \text{ GeV} \leq Q \leq 90 \text{ GeV} < M$$

that is below the threshold of Z boson. The results are summarized in table 2. For $Q \sim 90$ GeV

$$\frac{\frac{s\,d\sigma}{d\sqrt{\tau}dy}\Big|_{E_2^+E_2^-}}{\frac{s\,d\sigma}{d\sqrt{\tau}dy}\Big|_{\mu^+\mu^-}} \sim \frac{1}{2}$$

Table 2

Q in GeV	$\frac{s\,d\sigma}{d\sqrt{\tau}dy}\Big|_{y=0}^{E_2^+E_2^-}$ in μb	A
76	2×10^{-3}	0.25
78	$2{,}8 \times 10^{-3}$	0.34
80	$3{,}5 \times 10^{-3}$	0.38
83,2	$5{,}1 \times 10^{-3}$	0.44
90	$13{,}8 \times 10^{-3}$	0.46

$$\text{Here } A = \frac{\frac{s\,d\sigma}{d\sqrt{\tau}dy}\Big|^{E_2^+E_2^-}}{\frac{s\,d\sigma}{d\sqrt{\tau}dy}\Big|^{\mu^+\mu^-}} \quad \text{at } y = 0.$$

and $E_2^+E_2^-$ production probably is detectable as well. Thus, super-heavy leptons can be detected (if they exist) in $p\bar{p}$ collisions at energies available in the near future.

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