# Heavy-lepton production in a scalar model of weak interactions*

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The production of heavy leptons through the reaction $e^+e^- \to L^+L^-$ is considered in a model in which the weak interactions are mediated by the exchange of a heavy scalar. It is found that the weak contribution to the production cross section can be large, in fact, larger than the contribution from the electromagnetic interaction in some cases. Decays of the heavy leptons and angular correlations of their decay products are calculated.

## I. INTRODUCTION

Recently, Segrè[1] has revived an old model of weak interactions and shown that it is possible to have a renormalizable theory which is consistent with everything we know about weak interactions without the excess baggage (or beauty) of gauge symmetries, spontaneous breaking, etc. This model makes several interesting experimental predictions,[2,3] some of which are similar to predictions of some gauge theories but some of which seem to be unique. In particular, it predicts a large asymmetry in the scattering angle for the process $e^+e^- \to \mu^+\mu^-$, much larger than that predicted by gauge theories.[4]

An essential part of the model is heavy leptons, both charged and neutral, of undetermined mass. In this article we wish to consider the production, and subsequent decay, of a pair of charged heavy leptons through the process $e^+e^- \to L^+L^-$. This model gives a production cross section which is different from what one would get from just single-photon exchange,[5,6] perhaps drastically different. The decay of the heavy leptons, because their interactions are very restricted, is also much different from what is usually considered.[5,6]

In the next section we will define the model and calculate the production cross section as a function of energy, angles, and the polarizations of the particles. In Sec. III we will discuss this cross section and show how it may be very different from what one would expect. In Sec. IV we will discuss the decay rates of the heavy leptons, and in Sec. V we will use the spin dependence of the production cross section and decay rates to discuss correlations of the decay products.[5]

## II. DEFINITION OF THE MODEL AND CALCULATION OF THE CROSS SECTION

The interaction Lagrangian is[1]

$$\mathcal{L} = -i\Big\{\sum_{l=e,\mu} [f_0\overline{L}_l(1-\gamma_5)lB^0 + f_+\overline{L}_l(1-\gamma_5)\nu_l B^-] + f_+[\overline{\mathfrak{N}}_C(1-\gamma_5)\mathcal{P} + \overline{\lambda}_C(1-\gamma_5)\mathcal{P}']B^- + f_0[\overline{\mathfrak{N}}_C(1-\gamma_5)\mathfrak{N}_C + \overline{\lambda}_C(1-\gamma_5)\lambda_C]B^0\Big\} + \text{H.c.}\,, \qquad (2.1)$$

where the values of $l$ are the usual leptons, $e$ and $\mu$, while $\nu_l$ are the usual neutrinos. $L_l$ are two massive, charged leptons, and $B^0$, $\overline{B}^0$, and $B^\pm$ are the scalar mesons which mediate the interaction. The interactions with baryons are given in terms of the quarks $\mathcal{P}, \mathfrak{N}, \lambda, \mathcal{P}'$, where $\mathfrak{N}_C = \mathfrak{N}\cos\theta + \lambda\sin\theta$ and $\lambda_C = -\mathfrak{N}\sin\theta + \lambda\cos\theta$. There may also be couplings of $\overline{\mathcal{P}}\mathcal{P}$ and $\overline{\mathcal{P}}'\mathcal{P}'$ to $B^0$; these are not important for our purposes.

The lowest-order diagrams for $\mu$ and $\beta$ are shown in Fig. 1. If the masses of the scalar mesons are much larger than those of the heavy leptons and $m_{B^+} - m_{B^0} < m_{B^0}$ or $m_{B^+}$ then these box diagrams reduce to an effective $V-A$ interaction

$$H_{\text{eff}} = \frac{G}{\sqrt{2}}\bar{e}\gamma^\alpha(1-\gamma_5)\nu_e\bar{\nu}_\mu\gamma_\alpha(1-\gamma_5)\mu\,, \qquad (2.2)$$

where, if $f_+ \neq f_0$ but the mass of the charged scalar, $m_+$, is equal to the mass of the neutral scalar, $m_0$,

$$\frac{G}{\sqrt{2}} = \left(\frac{f_+f_0}{4\pi}\right)^2\frac{1}{m^2}\,, \qquad (2.3a)$$

or, if $f_+ = f_0 = f$ but $m_+ \neq m_0$,

$$\frac{G}{\sqrt{2}} = \left(\frac{f^2}{4\pi}\right)^2\frac{1}{m_+^2 - m_0^2}\ln\frac{m_+^2}{m_0^2}\,. \qquad (2.3b)$$

An effective neutral hadronic current can be calculated by considering the box graphs for lepton

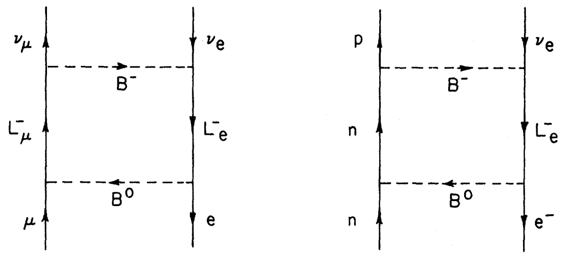


FIG. 1. Lowest-order diagrams for $\mu$ and $\beta$ decay.

quark elastic scattering. These boxes involve the exchange of two charged scalar mesons. The process $\nu+N\rightarrow\nu+$anything can then be calculated and compared with experiment. This indicates that the exchange of a charged $B$ meson should be suppressed relative to the exchange of a neutral $B$.[1,3] This suppression can be included in (2.3) either by setting $f_+{}^2=\epsilon f_0{}^2$ in (2.3a) with $\epsilon^2\approx\frac{1}{10}$ or by using $R\equiv m_+{}^2/m_0{}^2$ in (2.3b) with $R\approx 20$.

The suppression of charged-$B$ exchange acts to effectively enhance processes where only neutral scalars are exchanged. For example, the neutral-current effects in $e^+e^-\rightarrow\mu^+\mu^-$ are enhanced to the point where they are 6 to 12 times larger[3] than in the Weinberg-Salam model.[4] The weak contribution to the process $e^+e^-\rightarrow L^+L^-$ proceeds by the exchange of a single neutral scalar and therefore is also enhanced.

Also notice the $1/4\pi$ factors in (2.3). These arise in the definition of $G$ because of the loop integration associated with the box graph. The process $e^+e^-\rightarrow L^+L^-$ requires only $B$ exchange in the cross channel, not a closed loop, and therefore is enhanced by some factors of $4\pi$.

The matrix element for $e^+e^-\rightarrow L^+L^-$ is

$$M=\frac{e^2}{(p_1+p_2)^2}\bar{u}_L(p_3)\gamma^\mu v_L(p_4)\bar{v}_e(p_2)\gamma_\mu u_e(p_1)+\frac{f^2}{(p_1-p_3)^2-m_0{}^2}\bar{u}_L(p_3)(1-\gamma_5)u_e(p_1)\times\bar{v}_e(p_2)(1+\gamma_5)v_L(p_4)\,. \tag{2.4}$$

We work in the center-of-mass frame with the initial electron directed along the $z$ axis. The electron and positron have equal and opposite polarizations, $s$, which are perpendicular to their direction of motion. The direction of $s$ defines the $x$ axis

$$p_1^\mu=(E,0,0,E)\,, \tag{2.5a}$$

$$p_2^\mu=(E,0,0,-E)\,, \tag{2.5b}$$

$$s^\mu=(0,s,0,0)\,. \tag{2.6}$$

The heavy leptons are unstable, and one thing we wish to investigate is the correlation between the spin of the heavy leptons and the angular distribution of their decay products. Since the momenta are

$$p_3^\mu=(E,p\sin\theta\cos\phi,p\sin\theta\sin\phi,p\cos\theta)\,, \tag{2.7a}$$

$$p_4^\mu=(E,-p\sin\theta\cos\phi,-p\sin\theta\sin\phi,\;-p\cos\theta)\,, \tag{2.7b}$$

we define the spin vectors as

$$s_3^\mu=(\beta\gamma s_z,\,s_x\cos\theta\cos\phi-s_y\sin\phi+\gamma s_z\sin\theta\cos\phi,\,s_x\cos\theta\sin\phi+s_y\cos\phi+\gamma s_z\sin\theta\sin\phi,\gamma s_z\cos\theta-s_x\sin\theta)\,, \tag{2.8a}$$

$$s_4^\mu=(-\beta\gamma s_z',\,s_x'\cos\theta\cos\phi-s_y'\sin\phi+\gamma s_z'\sin\theta\cos\phi,\,s_x'\cos\theta\sin\phi+s_y'\cos\phi+\gamma s_z'\sin\theta\sin\phi,\gamma s_z'\cos\theta-s_x'\sin\theta)\,, \tag{2.8b}$$

where $\beta=(1-M_L{}^2/E^2)^{1/2}$ and $\gamma=E/M_L$.

The expression for the cross section is rather complicated, so let us write the contribution from the photon, the weak contribution, and the cross term separately:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm total}=\left(\frac{d\sigma}{d\Omega}\right)_\gamma+\left(\frac{d\sigma}{d\Omega}\right)_{\gamma W}+\left(\frac{d\sigma}{d\Omega}\right)_W. \tag{2.9}$$

The photon part is

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)_\gamma=\frac{\alpha^2}{16E^2}\beta\Big\{&1+\cos^2\theta+\frac{\sin^2\theta}{\gamma^2}-\beta^2\sin^2\theta s^2\cos2\phi+s_zs_z'\left[1+\cos^2\theta-\frac{\sin^2\theta}{\gamma^2}-\left(1+\frac{1}{\gamma^2}\right)\sin^2\theta s^2\cos2\phi\right]\\&+s_xs_x'\left[\left(1+\frac{1}{\gamma^2}\right)\sin^2\theta-(\beta^2\sin^2\theta+2\cos^2\theta)\,s^2\cos2\phi\right]+s_ys_y'[-\beta^2\sin^2\theta+(2-\beta^2\sin^2\theta)s^2\cos2\phi]\\&+(s_zs_x'+s_xs_z')\left(-\frac{1}{\gamma}\sin2\theta-\frac{1}{\gamma}\sin2\theta s^2\cos2\phi\right)\\&+(s_xs_y'+s_ys_x')(2\cos\theta s^2\sin2\phi)+(s_zs_y'+s_ys_z')\left(2\frac{1}{\gamma}\sin\theta s^2\sin2\phi\right)\Big\}\,.\end{aligned} \tag{2.10}$$

This cross section was given by Tsai[5] for the $s^2=0$ case.

If we use (2.3b) with $R\equiv m_+{}^2/m_0{}^2$ then the cross term is

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma W}=-\frac{G}{\sqrt{2}}\,\alpha\,\frac{4\pi}{f^2}\,\frac{R-1}{\ln R}\,\frac{\beta}{4}\Big\{2-2\beta\cos\theta-\beta^2\sin^2\theta+s_xs_x'(2-\beta^2)\sin^2\theta-s_ys_y'\beta^2\sin^2\theta$$
$$+(s_xs_z'+s_zs_x')\frac{\sin\theta}{\gamma}(\beta-2\cos\theta)$$
$$+s_zs_z'[(\gamma^2+1-\beta^2)\cos^2\theta-\gamma^2\beta^4-2\beta\cos\theta]$$
$$+(s_x+s_x')(\beta\sin\theta\cos\theta-2\sin\theta)\frac{1}{\gamma}+(s_z+s_z')[2\cos\theta-\beta(1+\cos^2\theta)]\Big\}$$
$$+\frac{G}{\sqrt{2}}\,\alpha\,\frac{4\pi}{f^2}\,\frac{R-1}{\ln R}\,\frac{\beta}{4}\,s^2\Big\{\beta^2\sin^2\theta\cos2\phi$$
$$+s_xs_x'[\sin^2\theta(2-\beta^2\sin^2\theta)+(\beta^2\sin^2\theta\cos^2\theta-2\cos\theta)\cos2\phi]$$
$$+s_ys_y'(-2+2\beta\cos\theta+\beta^2\sin^2\theta)\cos2\phi$$
$$+(s_xs_y'+s_ys_x')[\beta(1+\cos^2\theta)-2\cos\theta]\sin2\phi$$
$$+(s_ys_z'+s_zs_y')\frac{\sin\theta}{\gamma}(\beta\cos\theta-2)\sin2\phi$$
$$+(s_xs_z'+s_zs_x')\gamma\sin\theta[\beta^2\sin^2\theta(\cos\theta-\beta)$$
$$+\cos2\phi((2-\beta^2)\cos\theta-\beta+\beta^3\cos^2\theta-\beta^2\cos^3\theta)]$$
$$+s_zs_z'\sin^2\theta[-\beta^2\gamma^2+(2-\beta^2)\cos2\phi]$$
$$-\frac{\beta}{\gamma}[(s_x+s_x')\sin\theta\cos\theta\cos2\phi-(s_y+s_y')\sin\theta\sin2\phi+(s_z+s_z')\gamma\sin^2\theta\cos2\phi]\Big\}\,. \tag{2.11}$$

This part of the cross section already has the possibility of contributing significantly when compared with the photon term. The quantity

$$X=\frac{4\pi}{f^2}\,\frac{R-1}{\ln R} \tag{2.12}$$

is likely to be large because $f^2/4\pi\lesssim 1$ and $R$ is probably as large as 20.[3] Even if this factor is unity the ratio of the coefficient in (2.11) to that of (2.10) is 5.4% at $E=3.5$ GeV.

Equation (2.12) uses the $R$ formulation of the theory as in (2.3b). If we used the $\epsilon$ formulation of (2.3a) we would have

$$X=\frac{4\pi}{f_+{}^2}=\frac{1}{\epsilon}\,\frac{4\pi}{f_0{}^2}\ .$$

The final term in (2.9) is [using the definition in (2.12)]

$$\left(\frac{d\sigma}{d\Omega}\right)_{W}=\left(\frac{G}{\sqrt{2}}\right)^2E^2\beta X^2\Big[(1-\beta\cos\theta)^2+s_xs_x'\frac{1}{\gamma^2}\sin^2\theta+(s_xs_z'+s_zs_x')\frac{1}{\gamma}\sin\theta(\beta-\cos\theta)+s_zs_z'(\beta-\cos\theta)^2$$
$$+(s_x+s_x')\frac{1}{\gamma}\sin\theta(1-\beta\cos\theta)+(s_z+s_z')(1-\beta\cos\theta)(\beta-\cos\theta)\Big]\,. \tag{2.13}$$

Notice that this weak contribution is independent of $s^2$.

## III. PRODUCTION CROSS SECTION

The contribution to the production of a pair of heavy leptons from the weak interaction of (2.1) can be very large compared to the contribution from the electromagnetic interaction. To see this, consider the total cross section, as given by (2.10), (2.11), and (2.13), in the case where the polarizations of the final particles are not measured,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{total}}=\frac{\alpha^2}{16E^2}\beta\left(1+\cos^2\theta+\frac{\sin^2\theta}{\gamma^2}-\beta^2\sin^2\theta s^2\cos 2\phi\right)$$
$$-\frac{G}{\sqrt{2}}\,\alpha X\frac{\beta}{4}(2-2\beta\cos\theta-\beta^2\sin^2\theta-s^2\beta^2\sin^2\theta\cos 2\phi)+\left(\frac{G}{\sqrt{2}}\right)^2X^2E^2\beta(1-\beta\cos\theta)^2\,, \qquad (3.1)$$

and calculate the ratio of integrated cross sections,

$$\text{\textcal{R}}\equiv\frac{\int_{\Delta\Omega}\left(\frac{d\sigma}{d\Omega}\right)_{\text{total}}d\Omega}{\int_{\Delta\Omega}\left(\frac{d\sigma}{d\Omega}\right)_{\gamma}d\Omega}\,. \qquad (3.2)$$

If we take $\Delta\Omega$ as $0\le\phi\le 2\pi$, $-\frac{1}{2}\le\cos\theta\le\frac{1}{2}$, then $\mathcal{R}$ is equal to

$$1-\frac{G}{\sqrt{2}}X\frac{4}{\alpha}E^2+\left(\frac{G}{\sqrt{2}}\right)^2X^2\frac{16}{\alpha^2}E^4\frac{12+\beta^2}{24-11\beta^2}.$$

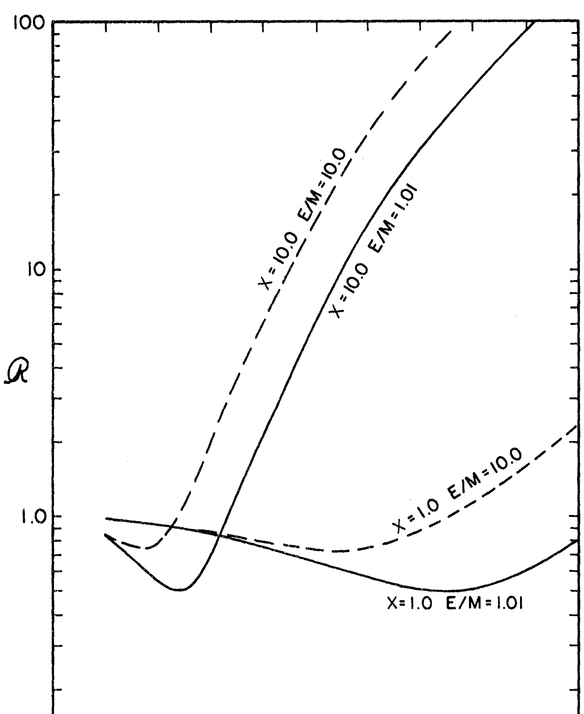


FIG. 2. $\mathcal{R}$ is the ratio of the differential cross section for $e^+e^-\to L^+L^-$ when both electromagnetic and weak interactions are included, to the same cross section when only single-photon exchange is included. $E$ is the beam energy and two values of $E/M_L$ are given to show that there is only a slight dependence on how far the energy is above threshold. $X$ is the one function of masses and coupling constants. The values of $X$ are intended for illustration only; $X$ is probably larger than 6.

A graph of $\mathcal{R}$ as a function of the energy is given in Fig. 2. Two values of $E/M_L$ are shown, one value just above threshold and one value far above threshold. The values of $X$ were chosen for illustrative purposes and are rather conservative; $X$ is more likely to range between 6 and 60.

Figure 2 shows that the cross section for the production of a heavy lepton pair is drastically different, for almost all $X$, $E$, and $M_L$, from what one would get from just the electromagnetic interaction. This will have a drastic effect on $R$, the ratio of $e^+e^-\to$ (anything except $\mu^+\mu^-$) to $e^+e^-\to\mu^+\mu^-$. Rather than adding to $R$ a factor of $\beta_L=(1-M_L^2/E^2)^{1/2}$ once $E$ exceeds the threshold for $L^+L^-$ production, as would be expected if the mechanism for producing $L^+L^-$ were the same as for producing $\mu^+\mu^-$, the number added to $R$ will vary between $\frac{1}{2}$ and something very large. Further, the number added to $R$ will grow as $\beta E^2$ for large $E$ because of the last term in (3.1).

## IV. DECAY RATES

Because the possible interactions of the $L$ are so severely limited in this model, $L$ can only decay into leptons through some high-order interaction such as that shown in Fig. 3. Therefore, the $L^\pm$, once produced, will decay semileptonically through the interaction shown in Fig. 4. This means they will live a relatively long time, much longer than in ordinary models of weak interactions. The decay rate for the process of Fig. 4, where the ordinary lepton is charged, is

$$\Gamma=\frac{16}{\pi}G^2m_q^{\,4}X^2M_L\frac{1}{a^2}I(a)\,, \qquad (4.1)$$

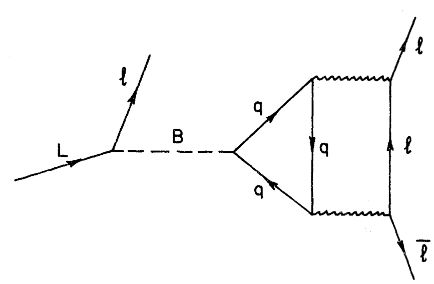


FIG. 3. Lowest-order diagrams for leptonic decay of the $L$. If the $B^0$ couples to $\bar{\mathcal{P}}\mathcal{P}$ and $\bar{\mathcal{P}}'\mathcal{P}'$, as it does in some version of the theory (see Ref. 1), then the wavy lines can be photons. Otherwise, the wavy lines are also scalar $B$ particles. The $q$ lines are quarks.

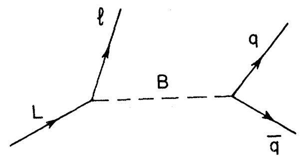


FIG. 4. Lowest-order diagrams for semileptonic decay of the $L$.

$$a \equiv \frac{M_L^2}{4m_q^2}, \tag{4.2}$$

where we have taken $m_q = m_{\bar{q}}$. Since the exchange of a charged $B$ is considerably suppressed relative to the exchange of a neutral $B$, the heavy lepton will decay into an electron or muon rather than a neutrino. $I(a)$ is a phase-space factor

$$I(a) = \tfrac{1}{4}\left(\frac{a-1}{a}\right)^{1/2}\left(\tfrac{1}{3}a^4 - \tfrac{7}{6}a^3 - \tfrac{1}{24}a^2 - \tfrac{1}{16}a\right) + \tfrac{1}{8}\left(a^2 - \tfrac{1}{16}\right)\ln\left[\frac{\sqrt{a} + (a-1)^{1/2}}{\sqrt{a} - (a-1)^{1/2}}\right]. \tag{4.3}$$

For example, if $M_L = 2$ GeV and $m_q = m_{\bar{q}} = 0.938$ GeV then the lifetime is

$$\tau = 1.1 \times 10^{-11}\frac{1}{X^2}\ \text{sec}.$$

The decay length of this particle, if it were produced at 15 GeV, would be

$$R = \gamma\beta c\tau = \frac{2.4}{X^2}\ \text{cm}.$$

Because of the numbers we have chosen, these values for $\tau$ and $R$ are upper limits on the possible lifetime and decay length.

The matrix element for decay of an $L^\pm$ goes as

$$(1 \pm \vec{s}_L \cdot \vec{\beta}_l)\, p_q \cdot p_{\bar{q}}, \tag{4.4}$$

where $s_L$ is the spin of the $L^\pm$ and $\vec{\beta}_l$ is the velocity of the ordinary lepton. Thus the lepton prefers to come out along the direction of the spin of the $L^+$ or opposite the direction of the spin of the $L^-$.

## V. DECAY CORRELATIONS

It is important to know the combined angular distribution of the decay products of the $L^-$ and $L^+$ at a given production angle. Tsai[5] has discussed this in detail for the case where the $L^\pm$ are produced by a single-photon exchange [Eq. (2.10)]. For clarity, let us briefly repeat his discussion. The angular distributions of the decay products of a polarized $L^-$ and $L^+$ are given by

$$\frac{d\Gamma(L^-)}{d\Omega} = A + B\vec{q}\cdot\vec{w}, \tag{5.1}$$

$$\frac{d\Gamma(L^+)}{d\Omega'} = A' + B'\vec{q}\,'\cdot\vec{w}\,', \tag{5.2}$$

where $q$ and $q'$ are the momenta of the decay products to be detected.

The production cross section is given by

$$\frac{d\sigma}{d\Omega_L} = C + D_{ij}s_i s_j' \tag{5.3}$$

[for example, see (2.10)]. The $w$ in (5.1) is the polarization vector of the $L^-$ defined by

$$w_i = \frac{\text{No. of } L^- \text{ polarized along } \hat{e}_i - \text{No. of } L^- \text{ polarized along } -\hat{e}_i}{\text{No. of } L^- \text{ polarized along } \hat{e}_i + \text{No. of } L^- \text{ polarized along } -\hat{e}_i}. \tag{5.4}$$

From (5.3) $w_i$ is given by

$$w_i = \frac{D_{ij}s_j'}{C}. \tag{5.5}$$

Putting this into (5.1) we have that the angular distribution of the decay products of $L^-$ is proportional to

$$CA + BD_{ij}q_i s_j'. \tag{5.6}$$

Now for a fixed angular distribution of the decay products of $L^-$ we can use (5.6) to find the polarization vector for $L^+$,

$$w_j' = \frac{BD_{ij}q_i}{AC}. \tag{5.7}$$

Putting this into (5.2) we have the combined angular distribution proportional to

$$CAA' + BB'D_{ij}q_i q_j'. \tag{5.8}$$

The properly normalized expression, as given by Tsai,[5] is

$$\frac{d\sigma}{d\Omega_L d\Omega d\Omega'} = \frac{CAA' + BB'D_{ij}q_i q_j'}{\Gamma_{\text{total}}^2}, \tag{5.9}$$

where $\Gamma_{\text{total}}$ is the total width of the $L^\pm$.

Now we want to apply this to our model. First we notice from (4.4) that, whatever the method of production, there will be no correlation unless it is the leptonic decay products that are detected because $B$ and $B'$ are only nonzero for the leptons.

Consider the case where the dominant method of production is one-photon exchange; the cross section in (2.10) dominates those of (2.11) and (2.13). If we ignore the $s^2$ dependence then this is the case discussed in detail by Tsai.[5] The only thing different here is the form of the decay rate. Equation (4.4) shows that the correlation is directly proportional to the velocity of the lepton. The polarization of the initial particles will not change anything unless the azimuthal production angle, $\phi$, is somehow measured since, in (2.10), $s^2$ is always multiplied by $\sin 2\phi$ or $\cos 2\phi$.

Now consider the more likely case that the production is dominated by the weak contribution of (2.13). In this case the cross section has additional terms, linear in the spin $s$ or $s'$, so that (5.3) must be replaced by

$$C+D_{ij}s_is'_j+E_i(s_i+s'_i)\,. \tag{5.10}$$

The polarization, defined by (5.4), is given by

$$w_i=\frac{D_{ij}s'_j+E_i}{C+E_is'_i}\,. \tag{5.11}$$

Using (5.11) the polarization of the $L^+$ is proportional to

$$w'_i \sim CD_{ij}q_j-E_iE_jq_j\,. \tag{5.12}$$

But, using the values of $D_{ij}$ and $E_i$ from (2.13), this is zero for all values of $\beta$, $\gamma$, and $\theta$. There is no correlation if (2.13) dominates the production, regardless of the decay process.

## VI. DISCUSSION

We have the following three main results:

(1) If this model is to be sensible then $X$, as defined in (2.12), must be larger than 1. Therefore, the cross section for producing a heavy-lepton pair must be considerably different from what is predicted on the basis of single-photon exchange and will be much larger than single-photon exchange once the beam energy is high enough. This is true as soon as the energy passes threshold and will cause a large change in $R$.

(2) The heavy leptons will decay almost entirely into a semileptonic mode and thus will live for a relatively long time.

(3) Once the production cross section is significantly different from that based on one-photon exchange, there will be no angular correlation of the decay products.

One (perhaps fatal) flaw in this model is its inability to explain the $e\mu$ events that are currently being seen,[7] as decays of the heavy leptons. An $e\mu$ could exist in a final state through an interaction such as that shown in Fig. 3, but the matrix element is suppressed, relative to the interaction of Fig. 4, by $G$ or $\alpha^2$. Of course the phase space will be larger, which could make up some of the difference unless, as is done in the data described in Ref. 7, a large cut is made in the energy.

Finally, quite apart from the weak-interaction model, the photon cross section given in (2.10) improves on the one given by Tsai[5] by including the dependence on the polarization of the initial particles.

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