PHYSICAL REVIEW D VOLUME 17, NUMBER 7 1 APRIL 1978

Electron-type neutral heavy lepton and the W-boson mass

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(Received 3 March 1977)

We comment on the experimental implications of the possible existence of an electron-type neutral heavy lepton E^0 with a mass around 10 GeV at the next generation of e^+e^- colliding machines with $\sqrt{s}=30$–40 GeV. The $e\mu$ decay signal from $E^0 \to e^- + \mu^+ + \nu_\mu$ following the *weak* production $e^+e^- \to \bar{\nu}_e + E^0$ is almost comparable to the $e\mu$ signal from the conventional charged heavy leptons produced via one-photon annihilation. (This is so because the small leptonic branching ratio enters only once for E^0 decay). The collinearity angle distributions of $e\mu$ signals from these two processes are quite distinct. The $e\mu$ cross section via E^0 production is rather sensitive to the mass of the W boson. The invariant-mass spectrum of $e\mu$ and the energy spectra of e and μ also show characteristic behaviors.

I. INTRODUCTION

There exist several experimental indications[1,2] of the possible existence of leptons and quarks beyond the standard four leptons and four quarks. One of the interesting schemes to unify these increasing numbers of elementary fermions is the idea of vectorlike currents[3,4] (but not necessarily purely vectorial currents).

In the present note, we comment on the experimental implications of the possible existence of an electron-type neutral heavy lepton E^0, which is required by the class of models to realize the idea of vectorlike currents (or left-right symmetry at short distances). Apart from these theoretical speculations, this neutral heavy lepton is interesting because it would give rise to a quite prominent $e\mu$ signal at the next generation of e^+e^- colliding machines, PEP and PETRA, with $\sqrt{s}=30-40$ GeV if the mass of E^0 is not so large (say $\lesssim 10$ GeV).[5] This process would provide one of those few *weak* processes which can compete with the dominant electromagnetic processes at these energies. This is so because the small leptonic branching ratio enters only once for E^0 decay and, consequently, $e\mu$ signals are relatively enhanced.

In the following we make these observations made in Ref. 5 more concrete by presenting a detailed calculation of various distributions.

II. $e\mu$ SIGNALS AND THEIR DEPENDENCE ON THE W MASS

We use a general phenomenological charged weak current for the neutral lepton E^0 in the present study, namely

$$J_\mu(x) = \bar{E}^0(x)\gamma_\mu[(1+\gamma_5)\cos\delta + (1-\gamma_5)\sin\delta]e(x)\,, \quad (2.1)$$

where δ is a parameter which characterizes the structure of the weak current; $\delta=0$ and $\pi/2$ correspond to right-handed and left-handed currents, respectively. We are interested in the production process[5,6]

$$e^+ + e^- \to E^0 + \bar{\nu}_e \quad (2.2)$$

via t-channel W exchange shown in Fig. 1. We assume that the neutral current is approximately "diagonal" and it does not contribute much to (2.2). As for the coupling constant of the W boson to charged weak lepton currents, we normalize it for $\delta=0$ (i.e., right-handed current) at the value given by the model of Fritzsch, Gell-Mann, and Minkowski.[4] In this case the total production cross section of E^0 in Fig. 1 is given by[5,6]

$$\sigma(s,m,M,\delta) = \frac{G^2 s}{2\pi}\left(1-\frac{m^2}{s}\right)\left(\frac{M^2}{s}\right)^2 T(s,m,M,\delta)\,, \quad (2.3)$$

where

$$T(s,m,M,\delta) \equiv \frac{1}{M^2(M^2+s-m^2)}[\cos^2\delta\, s(s-m^2) + \sin^2\delta\,(s+M^2)(s+M^2-m^2)] - \sin^2\delta\left[\left(\frac{2s+2M^2-m^2}{s-m^2}\right)\ln\left(\frac{M^2+s-m^2}{M^2}\right)-1\right]. \quad (2.4)$$

In Eq. (2.3)

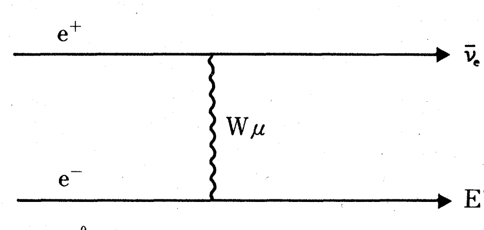

FIG. 1. E^0 production via t-channel W exchange in e^+e^- annihilation.

$s = 4E^2$ with E = incident electron energy,

M = mass of the W boson,

m = mass of E^0,

G = Fermi constant.

We also define the cross section

$$\sigma_0(s) \equiv \sigma(s, m, M = \infty, \delta = 0) = \frac{G^2 s}{2\pi}\left(1 - \frac{m^2}{s}\right)^2, \quad (2.5)$$

which corresponds to the cross section with an infinitely heavy W boson coupled to the right-handed heavy-lepton current. In Fig. 2, we show $\sigma_0(s)$ in units of the muon pair production cross section $\sigma(\mu\bar{\mu}) = 4\pi\alpha^2/3s$. See also Ref. 6. We see that $\sigma_0(s)/\sigma(\mu\bar{\mu})$ is about 6–20% for $\sqrt{s}$ = 30–40 GeV.

In Fig. 3, we show the cross section (2.3) in terms of $\sigma_0(s)$ in (2.5). We used M = 50 GeV in this calculation. This graph shows the dependence of the cross section on the W-boson mass and also on the structure of the weak current. The right-handed current gives rise to a considerably larger cross section than the left-handed current (this is the same effect as the famous factor-3 difference in νN and $\bar{\nu} N$ scattering). The effects of the finite W-boson mass is about 20% when one varies $\sqrt{s}$ from 30 to 40 GeV. It may therefore be possible to detect the effects of the finite W-boson mass in this process, although it would be difficult to determine the value of the W mass itself.

When one compares two processes

$$e^+ + e^- \to E^0 + \bar{\nu}_e \to e^- + \mu^+ + \bar{\nu}_e + \nu_\mu \quad (2.6a)$$

and

$$e^+ + e^- \to L + \bar{L} \to e + \mu + \nu_L + \bar{\nu}_L + \nu_e + \nu_\mu, \quad (2.6b)$$

the ratio of the $e\mu$ signals is given by

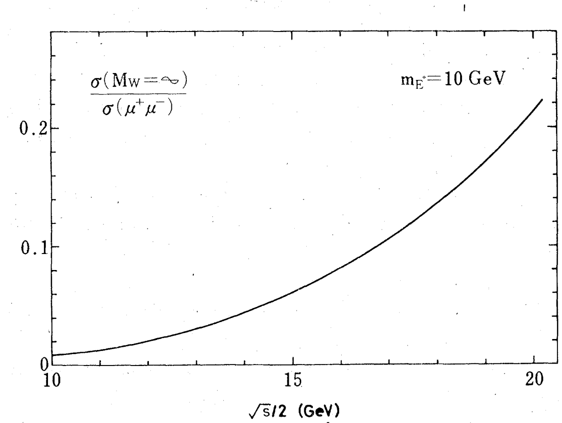

FIG. 2. The cross section (2.5) in units of the muon pair production cross section $\sigma(\mu\bar{\mu}) = 4\pi\alpha^2/3s$. The mass of E^0 is taken at 10 GeV.

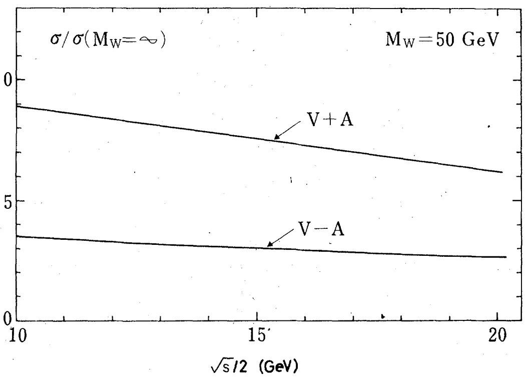

FIG. 3. The cross section (2.3) in terms of σ_0 in (2.5). The mass of E^0 is taken as 10 GeV. This graph shows the effects of the finite W mass.

$$R = \frac{[\sigma(E^0) + \sigma(\bar{E}^0)]\, B(E^0 \to e + \mu^+ + \nu_\mu)}{2\sigma(L\bar{L}) B(L \to \nu_L + \mu + \bar{\nu}_\mu)^2}, \quad (2.7)$$

where $B(E^0 \to e + \bar{\mu} + \nu_\mu)$ and $B(L \to \nu_L + \mu + \bar{\nu}_\mu)$ are the branching ratios for the corresponding leptonic decay modes.

If one identifies the U particle[1] with the heavy lepton L

$$B(L \to \nu_L + \mu + \bar{\nu}_L) \approx \tfrac{1}{6}. \quad (2.8)$$

On the other hand, a good guess of $B(E^0 \to e + \bar{\mu} + \nu_\mu)$ is

$$B(E^0 \to e + \bar{\mu} + \nu_\mu) \approx \tfrac{1}{10} \sim \tfrac{1}{12} \quad (2.9)$$

if the mass of E^0 is around 10 GeV. This estimate in (2.9) is made by counting the number of fundamental fermions expected in E^0 decay.

Combined with Fig. 2 (i.e., for the right-handed current), the ratio R in (2.7) is estimated at[5]

$$R = (20\text{–}60)\% \quad (2.10)$$

for $\sqrt{s}$ = 30–40 GeV. Although there are several uncertainties in this estimate of R, it is nevertheless encouraging that R is quite large at PEP and PETRA energies. We note that the production cross section of E^0 is not sensitive to the mass of E^0 as long as it is less than about 20 GeV. On the other hand, it strongly depends on the total incident energy in e^+e^- annihilation.

III. COLLINEARITY-ANGLE DISTRIBUTION OF $e\mu$

One of the most characteristic distributions which may allow us to distinguish two processes in (2.6) is the collinearity-angle distribution between e and μ. The collinearity angle is defined by

$$\cos\theta \equiv -(\vec{p}_e \cdot \vec{p}_\mu)/|\vec{p}_e||\vec{p}_\mu|. \quad (3.1)$$

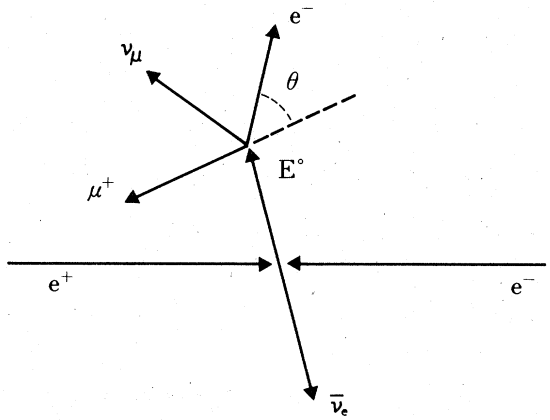

FIG. 4. Definition of the collinearity angle θ in E^0 production.

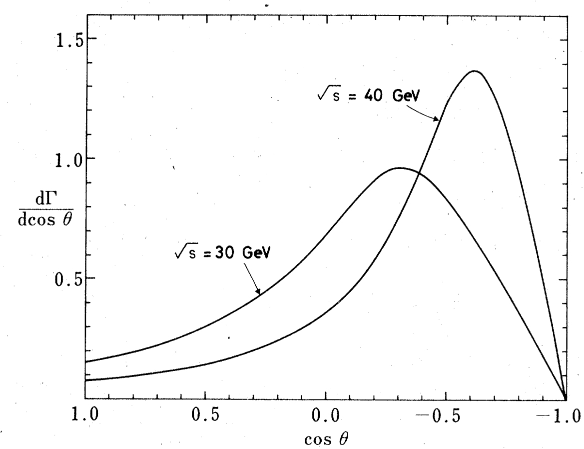

FIG. 5. Collinearity-angle distribution (3.2) in E^0 production. The mass of E^0 is taken as 10 GeV.

One can expect that $\cos\theta$ is concentrated near $\cos\theta = 1$ for $L\bar{L}$ production, and $\cos\theta$ is mainly distributed in the region $\cos\theta \leq 0$ for E^0 production.

To show those characteristic features more quantitatively, we calculate the collinearity-angle distribution for E^0 production in Fig. 4. For the *right-handed heavy-lepton current* [i.e., $\delta = 0$ in (2.1)], which is the most probable case if E^0 should exist, we obtain the normalized distribution

$$\frac{d\Gamma}{d\cos\theta} = \left(\frac{12}{\pi}\right)\frac{1}{(1-\cos\theta)^2} \times \int_{-1}^{1} d\cos\theta_1 \int_{-\pi}^{\pi} d\varphi\, F(\cos\theta_1, \varphi), \qquad (3.2)$$

where

$$F \equiv (10y^2 - 13y + \tfrac{10}{3}) + (10y^3 - 18y^2 + 9y - 1)\ln\left(1 - \frac{1}{y}\right) \qquad (3.3)$$

with

$$y \equiv \frac{2\gamma^2(1-\beta\cos\theta_1)(1-\beta\cos\theta_2)}{1-\cos\theta},$$

$$\cos\theta_2 \equiv \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos\varphi,$$

and β and γ are the Lorentz factors for E^0[$\gamma \equiv (s+m^2)/2m\sqrt{s}$]. The function F in (3.3) can also be written as

$$F \simeq \frac{1}{60}\frac{1}{y^3} + \frac{3}{140}\frac{1}{y^4} + \frac{3}{140}\frac{1}{y^5} + \frac{5}{252}\frac{1}{y^6} + \frac{1}{56}\frac{1}{y^7} + O\left(\frac{1}{y^8}\right) \qquad (3.4)$$

for $y \gg 1$.

In the calculation of (3.2), the masses of e and μ are neglected. We also integrated over all the kinematically allowed values of $\vec{p}_e$ and $\vec{p}_\mu$ with fixed $\cos\theta$. This corresponds to the detector system with a rather small energy cutoff and approximately 4π solid angles. We also neglected the effects of the finite W-boson mass.

The distribution is shown in Fig. 5 for $m = 10$ GeV. As is expected, the $\cos\theta$ distribution spreads over the wide angles. This behavior is in sharp contrast to the case of charged-heavy-lepton pair production, where the $\cos\theta$ distribution is limited within[7]

$$\cos\theta \gtrsim 1 - 4/\beta^2\gamma^2 \qquad (3.5)$$

with β and γ the Lorentz factors for the charged heavy lepton. If one uses $m_L \approx 2$ GeV at $\sqrt{s} \simeq 30$ GeV, (3.5) gives $\cos\theta \gtrsim \frac{15}{16}$.

It would therefore be quite easy to distinguish the two processes in (2.6), although there may appear several other background processes in the actual experiment.

IV. INVARIANT MASS OF $e\mu$ AND THE ENERGY SPECTRA OF e AND μ

Another characteristic property of E^0 decay is that the invariant mass of the $e\mu$ system is *independent* of the incident energy of the colliding beam. This is apparently not the case for charged-lepton pair production.

After a simple calculation, one obtains the normalized invariant-mass distribution for E^0 decay,

$$\frac{d\Gamma}{dx} = 24x(1-x^2)^2\left(x^2\cos^2\delta + \frac{1+2x^2}{6}\sin^2\delta\right), \qquad (4.1)$$

with $x \equiv m_{e\mu}/m$, m = mass of E^0. This is shown in Fig. 6.

For the sake of completeness, we also present the energy spectra of e and μ in the E^0 production. The muon spectrum is given by

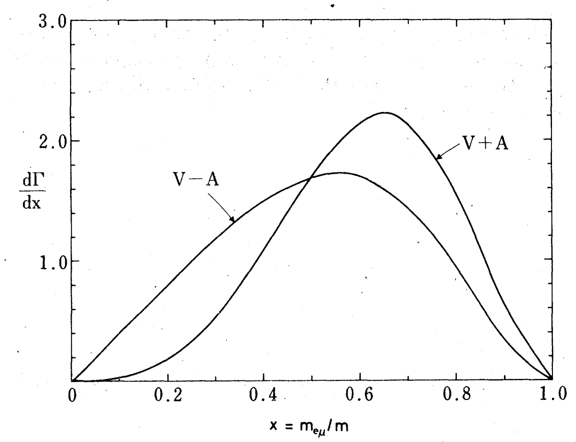

FIG. 6. Invariant-mass spectrum of the $e\mu$ system given by (4.1). The invariant mass $m_{e\mu}$ is normalized by the E^0 mass m.

$$\frac{d\Gamma}{dk}=\frac{4}{\sqrt{s}}F\left(1-\frac{2k}{\sqrt{s}}\right)\ \text{for}\ \frac{\sqrt{s}}{2}\geq k\geq\frac{m^2}{2\sqrt{s}}$$

$$=\frac{4}{\sqrt{s}}\left[F\left(1-\frac{2k}{\sqrt{s}}\right)-F\left(1-\frac{2\sqrt{s}\,k}{m^2}\right)\right]$$

$$\text{for}\ \frac{m^2}{2\sqrt{s}}\geq k\geq 0\,, \quad (4.2)$$

where

$$F(x)\equiv\cos^2\delta(x+\tfrac{1}{2}x^2-\tfrac{2}{3}x^3)+6\sin^2\delta(\tfrac{1}{2}x^2-\tfrac{1}{3}x^3) \quad (4.3)$$

and m is the mass of E^0. The electron spectrum is given by

$$\frac{d\Gamma}{dk}=\frac{4}{\sqrt{s}}G\left(1-\frac{2k}{\sqrt{s}}\right)\ \text{for}\ \frac{\sqrt{s}}{2}\geq k\geq\frac{m^2}{2\sqrt{s}}$$

$$=\frac{4}{\sqrt{s}}\left[G\left(1-\frac{2k}{\sqrt{s}}\right)-G\left(1-\frac{2\sqrt{s}\,k}{m^2}\right)\right]\ \text{for}\ \frac{m^2}{2\sqrt{s}}\geq k\geq 0\,, \quad (4.4)$$

where

$$G(x)=x+\tfrac{1}{2}x^2-\tfrac{2}{3}x^3\,. \quad (4.5)$$

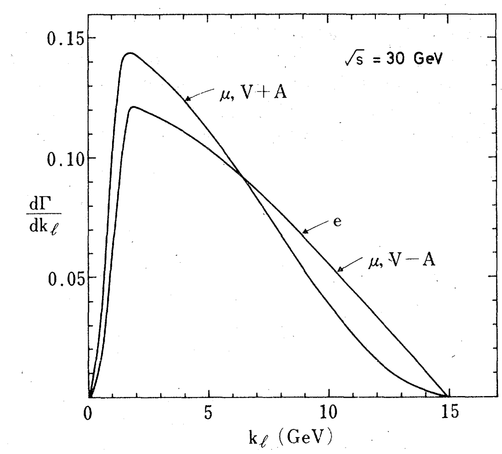

FIG. 7. Muon and electron energy spectra in E^0 decay. The mass of E^0 is taken as 10 GeV.

The electron spectrum is independent of the structure of the weak current (i.e., independent of δ). The energy spectra (4.2) and (4.4) are shown in Fig. 7.

The scaling property of the lepton energy spectra emphasized in Ref. 8 also appears in the high-energy part of (4.2) and (4.4). In fact, in the present case the scaling holds in terms of the simple Feynman variable $x\equiv 2k/\sqrt{s}$ as

$$\frac{d\Gamma}{dx}=2F(1-x)\ \text{for}\ 1\geq x\geq\frac{m^2}{s}\,. \quad (4.6)$$

Note added in proof. The production of E^0 in e^+e^- annihilation has been also discussed by Ahmed Ali, Phys. Rev. D 10, 2801 (1974).

ACKNOWLEDGMENT

I am grateful to H. Joos and T. Walsh for helpful comments at the early stage of the present work.

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