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NEUTRAL HEAVY LEPTONS AND e^+e^- COLLIDING BEAM EXPERIMENTS*

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ABSTRACT

The possibilities for detecting neutral heavy leptons N° in e^+e^- annihilation experiments are investigated. A detailed study of the important N°-decay modes is presented. The kinematical features of the reactions $e^+e^- \to N^\circ\bar{N}^\circ$ and $\bar{\nu}N^\circ$ with subsequent decay $N^\circ \to e\pi$ are explored with a view to deducing the heavy lepton couplings.

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I. INTRODUCTION

The last few years have witnessed remarkable activity[1] in the construction of unified gauge theory models of the weak and electromagnetic interactions. Confidence in the gauge theory approach has increased with the discovery of charm[2] and neutral currents,[3] both of which were essential ingredients of the original "minimal" SU(2) × U(1) model[4] incorporating the Glashow-Iliopoulos-Maiani mechanism.[5] However, the theoretical and experimental limitations of the minimal model have become increasingly evident. Charged current deep inelastic antineutrino-nucleon scattering shows a rise[6] in the ratio of antineutrino to neutrino cross sections $\sigma^{\bar{\nu}\bar{\mu}}/\sigma^{\nu\mu}$ and in the average of the inelasticity variable y. This anomalous behavior may be understood[7] as a consequence of the "defreezing" of a new quark degree of freedom b with right-handed weak coupling to the up quark u, leading to extensions of the minimal model to encompass new quark flavors. The leptonic sector experiences parallel enlargement with the postulation of neutral and charged heavy leptons. More direct impetus for new leptonic flavors has also been provided by recent experiments. The μe events observed in electron-positron annihilation[8] may be interpreted as products of the leptonic decays of pair-produced charged leptons U of mass 1.8-2.0 GeV. Further, measurements[9] of the optical rotation in Bismuth show atomic parity violation, which arises from interference of the leptonic axial vector and hadronic vector neutral currents, at a level well below that expected on the basis of the minimal model. It is therefore attractive to consider models in which the weak electronic neutral current is purely vector; such models require the existence of neutral heavy leptons with right-handed coupling to the electron and muon.[10] Such leptons have constantly reappeared in the construction of SU(2) × U(1) models with more than four quarks and leptons in order to maintain analogy

between the lepton and the hadron sector.[1] Renewed phenomenological interest in their existence has been stimulated by the recent experimental search for the $\mu \to e+\gamma$ decay;[11] a theory accommodating neutral heavy leptons with right-handed coupling to the electron and the muon naturally predicts lepton flavor changing processes.

These particles are expected to appear in the final state products of lepton induced deep-inelastic processes, in weak e^+e^- annihilation processes, in the decay of charmed particles and might eventually be detectable through decays of more massive charged heavy leptons and quarks.[12] Estimates for the production of neutral heavy leptons have been made in Refs. 12-15. The production rate in lepton-nucleon deep inelastic scattering is small, even at high energies. In e^+e^- annihilation, however, the production cross section rises essentially as s, at high energy becoming competitive with electromagnetic processes. In this paper, we assume the existence of neutral heavy leptons N° and study their production and the possibility of their detection in e^+e^- experiments.

The paper is organized as follows: in Section II we discuss the introduction of neutral heavy leptons in $SU(2) \times U(1)$ models which go beyond the structure of the simple minimal model. Section III is devoted to their production in e^+e^- annihilation; we investigate the dynamical consequences of charged and neutral boson exchange and determine the N° production cross section. The decay modes of N° are explored in Section IV. A distinctive decay signature is e (or μ) π. We therefore present in Section V a study of the dynamical characteristics of the reactions $e^+e^- \to \bar{\nu}(\text{or } \bar{N}^\circ)N^\circ_{\hookrightarrow e\pi}$ from which the mass and coupling of N° may be determined.[14] Our conclusions are summarized in Section VI.

II. MODEL CONSIDERATIONS

In the previous section we have briefly indicated the motivation for the introduction of new quark and lepton flavors. The present status of weak interaction physics allows latitude in the construction of models incorporating neutral heavy leptons. These models may be distinguished by the chirality of the coupling of the neutral heavy leptons to the electron and muon.

Much study has been devoted to "vector-like" SU(2) × U(1) models with the leptonic doublet structure[1,7,16],

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}E^o\\ e^-\end{pmatrix}_R, \begin{pmatrix}M^o\\ \mu^-\end{pmatrix}_R \tag{2.1}$$

E and M may be mixtures of the mass eigenstates N_1 and N_2 [16]:

$$\begin{aligned} E^o &= N_1^\circ \cos\Phi + N_2^\circ \sin\Phi \\ M^o &= -N_1^\circ \sin\Phi + N_2^\circ \cos\Phi \end{aligned} \tag{2.2}$$

The model may be extended as in Ref. 17 to include the sequential pair $(\nu_U, U^-)_L$. As pointed out by Cheng and Li,[16] the mixing (2.2) provides a natural mechanism for separate electron and muon number nonconserving processes such as $\mu \to e\gamma$ and $K_L \to e\mu$. The $\mu \to e\gamma$ decay rate is proportional to $(\sin 2\phi\ \Delta m^2_{N^\circ}/m^2_W)^2$; with, for example, the choice $\Phi = \pi/4$ and $\Delta m^2_{N^\circ} = 7\ \mathrm{GeV}^2$, the branching ratio $BR(\mu \to e\gamma) \simeq 10^{-9}$ is within the present experimentally accessible range.[11] The leptonic weak currents in this model are

$$\begin{aligned} j^W_\mu = {} & \bar\nu_e \gamma_\mu (1-\gamma_5) e + \bar\nu_\mu \gamma_\mu (1-\gamma_5)\mu + (\bar N_1^\circ \cos\Phi + \bar N_2^\circ \sin\Phi)\ \gamma_\mu (1+\gamma_5) e \\ & + (-\bar N_1^\circ \sin\Phi + \bar N_2^\circ \cos\Phi)\ \gamma_\mu (1+\gamma_5)\mu \end{aligned} \tag{2.3}$$

with coupling $\left(G_F M_W^2/\sqrt{2}\right)^{1/2}$ to the charged intermediate vector boson W, and

$$j_\mu^Z = \bar{N}_1^\circ \gamma_\mu (1+\gamma_5) N_1 + \bar{N}_2^\circ \gamma_\mu (1+\gamma_5) N_2^\circ + \bar{\nu}_e \gamma_\mu (1-\gamma_5) \nu_e$$
$$+ \left(4 \sin^2 \theta_W - 2\right) \bar{e} \gamma_\mu e + (e \to \mu) \qquad (2.4)$$

coupled to the neutral vector boson Z by $\frac{1}{\sqrt{2}}\left(G_F M_Z^2/\sqrt{2}\right)^{1/2}$. G_F is the Fermi constant: $G_F = 10^{-5}\, m_p^{-2}$, and θ_W is the Weinberg angle. Thus the right-handed coupling of the electron to a neutral heavy lepton ensures the absence of an axial vector contribution to the electronic neutral current. Consequently, atomic parity violation effects now arise from the interference of the electronic vector and hadronic axial vector currents and are suppressed to a level consistent with the Oxford-Washington results.[9] It is prudent, however, to bear in mind that there is considerable uncertainty[18] in the treatment of configuration mixing in the low-lying atomic states of Bismuth, upon which estimates of parity violating effects in weak interaction models depend. Thus we may still have the freedom to maintain the pure left-handed doublet structure and parity-violating neutral current characteristic of the minimal model.

An alternative extension[19,20] of the minimal model is the addition of a left-handed doublet $(N_U^\circ, U^-)_L$, where U^- may be identified with the Perl particle.[8] Diagonalization of the fermion mass matrix induces a mixing of the neutrinos with the more massive N_U°:

$$\begin{pmatrix} \nu_1 \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_2 \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \mathcal{N}^\circ \\ U^- \end{pmatrix}_L \qquad (2.5)$$

with

$$\nu_1 = \left(1 - \frac{\epsilon_e^2}{2}\right) \nu_e - \frac{1}{2}\, \epsilon_e\, \epsilon_\mu\, \nu_\mu - \epsilon_e N_U^\circ$$

$$\nu_2 = \left(1 - \frac{\epsilon_\mu^2}{2}\right)\nu_\mu - \frac{1}{2}\epsilon_e\epsilon_\mu\,\nu_e - \epsilon_\mu\,N_U^\circ$$

$$\mathcal{N}^\circ = N_U^\circ + \epsilon_e\,\nu_e + \epsilon_\mu\,\nu_\mu \tag{2.6}$$

The resultant violation of universality cannot experimentally exceed the one percent level, bounding the mixing parameters $\epsilon_{e,\mu} \lesssim 0.1$. Hence the coupling of e and μ to the neutral heavy lepton is suppressed with respect to the Fermi-strength coupling of the vector-like model: such a suppression is characteristic of models in which the e (μ)-N° coupling is left-handed. The leptonic neutral current of this model gives rise to parity violation:

$$j_\mu^Z = \sum_{\nu=\nu_e,\nu_\mu,N_U^\circ} \bar{\nu}\,\gamma_\mu(1-\gamma_5)\nu + \sum_{\ell=e,\mu,U} \bar{\ell}\gamma_\mu\left[\left(4\sin^2\theta_W - 1\right) + \gamma_5\right]\ell \tag{2.7}$$

The contribution of the light leptons is, of course, identical to that of the Weinberg-Salam model.[4] The $\mu \to e\gamma$ decay now occurs through an intermediate (N_U°, W^-) state, with the emission of a left-handed electron.

The two models summarized above illustrate a general feature: the electron and muon may couple in full strength only to right-handed neutral heavy leptons; left-handed coupling is suppressed by the constraint of universality.

What are the prospects for the detection of the neutral heavy leptons envisaged by models of the type (2.1) and (2.5)? Let us first consider N° of type (2.1). Although the production of N° in lepton-induced deep inelastic scattering, directly or as a weak decay product of a charmed particle, would give spectacular multimuon decay signatures, estimates of Refs. 12 and 13 give discouragingly small cross sections. On the other hand, the cross sections for the weak processes $e^+e^- \to \bar{\nu}N^\circ$ and $e^+e^- \to \bar{N}^\circ N^\circ$ are essentially linear in (center

of mass energy)^2 and give significant yields at high energies (see Section III). The properties of N° may then be inferred from the study of its jet-like decay products (see Section V). A heavy lepton N°_U of type (2.5) is more difficult to detect. It cannot be produced in neutrino scattering, since the neutral current (2.7) conserves lepton flavor. N°_U-production in charged lepton-induced scattering is inhibited by the smallness of the mixing parameter ϵ, as is single N° production in the process $e^+e^- \to \bar{\nu}N^\circ_U$. The neutral current reaction $e^+e^- \to Z \to N^\circ_U \bar{N}^\circ_U$ offers the best hope;[19] unfortunately, the cross section is small compared to the production of N° of type (2.1), where W exchange provides the main contribution off the Z resonance peak. A more immediate discriminant between schemes (2.1) and (2.5) is the observation of a deviation from unity of the ratio $\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e)/\sigma(\nu_\mu e \to \nu_\mu e)$ which signals the presence of an axial vector contribution to the electronic neutral current. The experimental situation is at present clouded.[21]

III. N°-PRODUCTION IN e^+e^- ANNIHILATION

In this section we study the production of neutral heavy leptons in e^+e^- colliding beams. We first calculate the cross section allowing general vector and axial vector coupling constants; later we specialize to the vector-like model (2.1) to present estimates of the production rate to be expected at SPEAR and PEP/PETRA energies.

N° may be produced singly

$$e^+e^- \to \bar{\nu}N^\circ \tag{3.1}$$

or in pairs

$$e^+e^- \to \bar{N}^\circ N^\circ \tag{3.2}$$

Single-N° production is mediated by the t-channel exchange of the charged intermediate vector boson W, while pair production receives contributions from

t-channel W exchange and the s-channel exchange of the neutral intermediate vector boson Z. We consider the generic reaction[22]

$$e^+e^- \to \bar{M}N^\circ \tag{3.3}$$

where $M = \nu$ or N° the relevant Feynman diagrams are shown in Fig. 1, where the kinematics are defined. The amplitude for (3.1) is $\mathcal{M} = \mathcal{M}_1$, and for (3.2) is $\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2$, where

$$\mathcal{M}_1 = i\bar{v}_e\gamma_\mu(a+b\gamma_5)\,v_M\,\mathcal{P}_W^{\mu\nu}\,\bar{u}_{N^\circ}\gamma_\nu(c+d\gamma_5)\,u_e \tag{3.4}$$

$$\mathcal{M}_2 = -i\bar{v}_e\gamma_\mu(e+f\gamma_5)\,u_e\,\mathcal{P}_Z^{\mu\nu}\,\bar{u}_{N^\circ}\gamma_\nu(g+h\gamma_5)\,v_M \tag{3.5}$$

with the minus sign in (3.5) originating from Fermi statistics. $\mathcal{P}_{W,Z}^{\mu\nu}$ are the W and Z propagators, respectively. It is straightforward to calculate the angular distribution of N°. We make the approximations $m_{N^\circ,M}^2 \ll m_W^2$, $m_e \simeq 0$. Then W exchange contributes

$$\frac{d\sigma_W}{d\cos\theta_{N^\circ}} = \frac{s}{64\pi}\,\frac{\xi}{\left(t-M_W^2\right)^2}\left\{\left(1-\frac{\alpha^2}{s^2}\right)(\Lambda_1+2\Lambda_2) + 2\xi^2\Lambda_2 + 2\xi\Lambda_1\cos\theta_{N^\circ} + \xi^2\Lambda_1\cos^2\theta_{N^\circ}\right\} \tag{3.6}$$

where

$$\Lambda_1 = (a^2+b^2)(c^2+d^2) + 4abcd$$

$$\Lambda_2 = (a^2+b^2)(c^2+d^2) - 4abcd$$

and

$$\xi = \left(\left[1-\frac{(m_{N^\circ}-m_M)^2}{s}\right]\left[1-\frac{(m_{N^\circ}+m_M)^2}{s}\right]\right)^{1/2}$$

$$\alpha = m_{N^\circ}^2 - m_M^2$$

θ_{N° is the angle between the directions of N° and the incident electron beam. The Z-exchange contribution is

$$\frac{d\sigma_Z}{d\cos\theta_{N^\circ}} = \frac{s}{64\pi}\,\frac{\xi}{\left(s-M_Z^2\right)^2+\Gamma_Z^2 M_Z^2}\left\{\left(1-\frac{\alpha^2}{s^2}\right)(\Lambda_3+\Lambda_4)\right.$$

$$+\frac{8}{s}m_{N^\circ}m_M\Lambda_5 + 2\xi(\Lambda_3-\Lambda_4)\cos\theta_{N^\circ}$$

$$\left.+\,\xi^2(\Lambda_3+\Lambda_4)\cos^2\theta_{N^\circ}\right\}\quad; \tag{3.7}$$

M_Z and Γ_Z are the mass and width of the Z-boson, and

$$\Lambda_3 = (e^2+f^2)(g^2+h^2) + 4efgh$$

$$\Lambda_4 = (e^2+f^2)(g^2+h^2) - 4efgh$$

$$\Lambda_5 = (e^2+f^2)(g^2-h^2)\quad .$$

Finally, the W-Z interference contribution gives

$$\frac{d\sigma_{int}}{d\cos\theta_{N^\circ}} = \frac{s}{32\pi}\,\frac{\xi\left(s-M_Z^2\right)}{\left(t-M_W^2\right)\left[\left(s-M_Z^2\right)^2+\Gamma_Z^2M_Z^2\right]}$$

$$\times\left\{-\frac{4m_{N^\circ}m_M}{s}\Lambda_6 + \left(1-\frac{\alpha^2}{s^2}\right)\Lambda_7\right.$$

$$\left.+\,2\xi\Lambda_7\cos\theta_{N^\circ}+\xi^2\Lambda_7\cos^2\theta_{N^\circ}\right\} \tag{3.8}$$

with

$$\Lambda_6 = (df+ec)(hb-ga) + (de+cf)(ha-gb)$$

$$\Lambda_7 = (df+ec)(hb+ga) + (de+cf)(ha+gb)\quad .$$

Having established our formalism, we specialize to reactions (3.1) and (3.2) and examine the influence of the heavy lepton couplings on its angular distribution. Consider first the reaction (3.1). For right-handed e-N° coupling, the angular

distribution (3.6) is isotropic[23] as expected from angular momentum considerations. In contrast, V-A coupling gives a characteristic $(1+\cos\theta_{N^\circ})^2$ behavior in the high energy regime $s \gg m^2_{N^\circ}$: a left-handed heavy lepton is produced preferentially in the forward direction. In the case of pure vector or axial vector coupling, $\Lambda_1 = \Lambda_2$ and the angular distribution at high energy behaves as $4+(1+\cos\theta_{N^\circ})^2$. The pair production reaction (3.2) is generally contributed to by both Z and W exchange (terms (3.6), (3.7) and (3.8)). In the high energy region, W exchange shows a $(1+\cos\theta_{N^\circ})^2$ behavior for both right and left (e, N) coupling, as does the interference term. The Z exchange term behaves as $(1+\cos\theta_{N^\circ})^2$ when the couplings at both vertices are left-handed; a (left × right) coupling produces a $(1-\cos\theta_{N^\circ})^2$ distribution. If either vertex is purely left- or right-handed, the distribution is $1+\cos^2\theta_{N^\circ}$. In the model defined by the assignment (2.5), Z-exchange is the only significant contribution to N°-pair production. The heavy leptons N°_U make a spectacular appearance in the reaction $e^+e^- \xrightarrow{Z} \bar{N}^\circ_U N^\circ_U$, followed by N°_U-cascade decays.[19] The reaction is, of course, greatly enhanced in the Z resonance region, $\sqrt{s} \simeq 80$ GeV.

To calculate the N°-production rate expected on the basis of the vector-like scheme (2.1), we can read off the values of the coupling constants from Eqs. (2.3) and (2.4). For purposes of comparison we shall also compute the cross section for a left-handed (e, N°) coupling of the same strength. Thus we introduce the parameter $\lambda = \pm 1$ for $V \pm A$ e-N° coupling and find

$$\frac{d\sigma}{d\cos\theta_{N^\circ}}(e^+e^- \to \bar{\nu}N^\circ_1) = \frac{G_F^2 s}{32\pi} \frac{\cos^2\Phi\left(1-m^2_{N^\circ}/s\right)^2}{\left(1-t/M_W^2\right)^2}$$

$$\times\left\{2(1+\lambda)\left(1-m^2_{N^\circ}/s\right) + (3+\lambda)\left(1+m^2_{N^\circ}/s\right) + 2(1-\lambda)\cos\theta_{N^\circ} + (1-\lambda)\left(1-m^2_{N^\circ}/s\right)\cos^2\theta_{N^\circ}\right\}$$

$$\equiv \cos^2\Phi \frac{d\hat{\sigma}}{d\cos\theta_{N^\circ}} \qquad (3.9)$$

$$\frac{d\sigma}{d\cos\theta_{N^\circ}}(e^+e^- \to \bar{N}^\circ_1 N^\circ_1) = \frac{G_F^2\,\beta s}{16\pi}\left\{\cos^4\Phi\,\frac{(1+\beta\cos\theta_{N^\circ})^2}{\left(1-t/M_W^2\right)^2}\right.$$

$$+\frac{1}{2}\cos^2 2\theta_W\,\frac{\left(1+\beta^2\cos^2\theta_{N^\circ}\right)}{\left(1-s/M_Z^2\right)^2+\Gamma_Z^2/M_Z^2}$$

$$\left.-\frac{\cos 2\theta_W\cos^2\Phi\left(1-s/M_Z^2\right)\left(1+\beta\cos\theta_{N^\circ}\right)^2}{\left(1-t/M_W^2\right)\left[\left(1-s/M_Z^2\right)^2+\Gamma_Z^2/M_Z^2\right]}\right\}$$

$$\equiv \cos^4\Phi\,\frac{d\hat{\sigma}_W}{d\cos\theta_{N^\circ}}+\frac{d\hat{\sigma}_Z}{d\cos\theta_{N^\circ}}+\cos^2\Phi\,\frac{d\hat{\sigma}_{int}}{d\cos\theta_{N^\circ}}\,, \quad (3.10)$$

where $\beta=\left(1-4m_{N^\circ}^2/s\right)^{1/2}$. In the case of N°_2 production, $\cos\Phi$ is replaced by $\sin\Phi$. The distributions (3.9) and (3.10), integrated over θ_{N° are plotted in Fig. 2 as functions of s with $\sin^2\theta_W=0.35$, $M_W=63$ GeV, $M_Z=78$ GeV and $\Gamma_Z=1.1$ GeV. For definiteness we take $\Phi=\pi/4$. Off threshold the cross sections are insensitive to m_{N°. Single-N°production outweighs N°-pair production by an order of magnitude outside the Z-resonance region, while pair production is obviously dominant around the Z, becoming $0(10^{-33}\ \mathrm{cm}^2)$ at the resonance peak. Changing V+A to V-A coupling does not affect the pair production cross section, whereas the single-N°channel is reduced by a factor 2-3. There is strong interference between W and Z exchange contributions, destructive below the Z-resonance and constructive above. The sign of the interference term depends on that of Λ_7 and hence on the model dependent choice of coupling parameters. For example in the model (2.1) the interference term becomes positive (negative) below (above) the Z-boson peak if $\sin^2\theta_W>0.5$; for $\sin^2\theta_W=0.5$ there is no interference. When $|m^2_{N^\circ_2}-m^2_{N^\circ_1}|\ll s$, the total production cross section

becomes independent of mixing angle and is

$$\sigma_{tot} = \sum_{i=1}^{2} \sigma(\bar{\nu} N_i^{\circ}) + \sigma(\nu \bar{N}_i^{\circ}) + \sum_{ij} \sigma(N_i^{\circ} \bar{N}_j^{\circ})$$

$$= 2(\hat{\sigma} + \hat{\sigma}_Z) + \hat{\sigma}_W + \hat{\sigma}_{int} \tag{3.11}$$

From Eqs. (3.9), (3.10), and (3.11) we estimate for a PEP/PETRA energy of $\sqrt{s}/2 = 16$ GeV and a projected luminosity of 10^{32} cm^{-2} sec^{-1} an N°-production rate of 120/day, of which 13% are pair produced. The corresponding results for $\lambda = -1$ and the rate at maximum SPEAR energy $\sqrt{s}/2 = 4$ GeV and luminosity 10^{31} cm^{-2} sec^{-1} are shown in Table I.

IV. N° DECAYS

In this section we investigate the major decay modes of a neutral heavy lepton coupled to e and μ with vector and axial vector couplings (c, d). The decay rates have been estimated following Ref. 24 and here we need only summarize our results.

A. Leptonic Decays

The width for each of the decays

$$N^{\circ} \to e^- + (e^+ \nu_e), \quad e^- + (\mu^+ \nu_\mu), \quad \mu^- + (e^+ \nu_e), \quad \mu^- + (\mu^+ \nu_\mu)$$

is, neglecting m_e and m_μ:

$$\Gamma = \frac{G_F \, m_{N^{\circ}}^5}{192\pi^3} \cdot \frac{c^2 + d^2}{\sqrt{2}\, M_W^2} \tag{4.1}$$

If sufficiently heavy, N° may decay into a charged heavy lepton U^+ through the decay mode $N^{\circ} \to e^-(\mu^-) + (U^+ \nu_U)$. The resulting width then reads

$$\Gamma = \frac{G_F \, m_{N^{\circ}}^5}{384\pi^3} \left[(2\alpha+\beta)\, f_1(z) - (3\alpha+\beta)\, f_2(z) - 4\beta f_3(z) \right] \tag{4.2}$$

where

$$\alpha = (c-d)^2/\sqrt{2}\, M_W^2$$

$$\beta = (c+d)^2/\sqrt{2}\, M_W^2$$

and in terms of $z = m_U/m_{N^\circ}$,

$$f_1(z) = 2(1-z^2)^3\,(1+z^2)$$

$$f_2(z) = (1+z^4)(1-z^4) + 8z^4 \ln z$$

$$f_3(z) = z^2(1-z^4) + 4z^4 \ln z \quad .$$

If mass differences permit, the decays of N° into a lighter neutral heavy lepton $N_2^\circ \to e^-(\mu^-) + N_1^\circ e^+(\mu^+)$ also occur with rate

$$\Gamma = \frac{m_{N_2^\circ}^5}{768\,\pi^3 M_W^4}\left[(2\alpha'+\beta')\,f_1(z) - (3\alpha'+\beta')\,f_2(z) - 4\beta'\,f_3(z)\right] \tag{4.3}$$

Here

$$\alpha' = \left(c_1^2+d_1^2\right)\left(c_2^2+d_2^2\right) + 4c_1d_1c_2d_2$$

$$\beta' = \left(c_1^2+d_1^2\right)\left(c_2^2+d_2^2\right) - 4c_1d_1c_2d_2$$

and $z = m_{N_1^\circ}/m_{N_2^\circ}$; c_i and d_i are the coupling parameters at the two vertices and $f_j(z)$ is defined above. This decay can give rise to distinctive multilepton signatures such as $\mu^+\mu^+\mu^-\mu^-$. We do not consider decays through Z emission, e.g., $N_2^\circ \to N_1^\circ$ + hadrons, since nondiagonal neutral currents are small induced mixing effects.

B. Exclusive Hadronic Decays

The major single-hadron channels are expected to be $N^\circ \to e(\mu) + \pi,\ \rho,\ A_1$, with widths

$$\Gamma(N^\circ \to e\pi) = 2f_\pi^2\, C\left(1 - m_\pi^2/m_{N^\circ}^2\right)^2 \tag{4.4}$$

$$\Gamma(N^\circ \to e\rho) = \frac{m_\rho^2}{\gamma_\rho^2} C\left(1 - m_\rho^2/m_{N^\circ}^2\right)^2 \left(1 + 2m_\rho^2/m_{N^\circ}^2\right) \tag{4.5}$$

$$\Gamma(N^\circ \to eA_1) = \frac{m_{A_1}^2}{\gamma_{A_1}^2} C\left(1 - m_{A_1}^2/m_{N^\circ}^2\right)^2 \left(1 + 2m_{A_1}^2/m_{N^\circ}^2\right) \tag{4.6}$$

where

$$C = \frac{G_F m_{N^\circ}^3}{32\pi}\left(\frac{c^2+d^2}{\sqrt{2}\, M_W^2}\right)$$

$f_\pi = 0.93\, m_\pi$, $\gamma_\rho^2/4\pi = 0.64$ and the second Weinberg sum rule[25] fixes $\gamma_{A_1} = \gamma_\rho m_{A_1}^2/m_\rho^2$.

C. Hadronic Continuum

The decay width for $N^\circ \to e(\mu)$ + hadronic continuum has been estimated in Refs. 24 and 26 using the spectral representation for the weak current-current tensor. Use is made of the hypothesis of conserved vector currents, asymptotic chiral symmetry and asymptotic SU(3), and the result is expressed in terms of the ratio

$$R = \lim_{s\to\infty} \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{4.7}$$

$$\Gamma(N^\circ \to e(\mu)+\text{continuum}) = \frac{G_F m_{N^\circ}^3}{64\pi^3}\left(\frac{c^2+d^2}{\sqrt{2}\, M_W^2}\right)\int_{\Lambda^2}^{m_{N^\circ}^2} ds \left(1 - \frac{s}{m_{N^\circ}^2}\right)\left(1 + \frac{s}{m_{N^\circ}^2} - \frac{2s^2}{m_{N^\circ}^4}\right) \tag{4.8}$$

where Λ characterizes the onset of the asymptotic regime. Guided by recent SPEAR results, we take $R = 2$ for $0.9 \leq \sqrt{s} \leq 4$ GeV and $R = 5$ for $\sqrt{s} > 4$ GeV.

Assembling the above results gives the total decay width as a function of the mass m_{N°, shown in Fig. 3. For numerical purposes, we have taken the values

of c and d as given by the model (2.1); in the approximation of neglect of $m_{e,\mu}$ dependence on the mixing angle Φ disappears. The branching ratios of the various modes discussed above are shown in Fig. 4. For $m_{N^\circ} \lesssim 1$ GeV, the $e(\mu)\pi$ channel dominates. As m_{N° is increased, leptonic decays dominate and the pion mode steadily decreases to the 5% level at $m_{N^\circ} \cong 3$ GeV. The hadronic continuum becomes more significant, giving an indirect contribution to the ratio R defined in Eq. (4.7). The branching ratio of N° into U(1.9) is around 10% for $m_{N^\circ} \simeq 6$ GeV. The absence of the decay $K \to N^\circ e$ places a lower bound of 0.5 GeV on the N° mass.

V. DETECTION OF N THROUGH THE DECAY $N^\circ \to \ell\pi$

As we have seen in Section IV, the decay channel $N^\circ \to \ell\pi$ ($\ell = e$ or μ) is dominant for $m_{N^\circ} \lesssim 1$ GeV, dropping to 5% at $m_{N^\circ} \sim 3$ GeV. If N° is relatively light, this two body decay mode offers a particularly clean signature for the detection and study of N°. The N°-momentum can be reconstructed from events with only a charged lepton and pion in the final state, allowing determination of the heavy lepton mass and scattering angle. Furthermore, the distribution of the decay products is sensitive to the chirality of the N°-ℓ coupling: the production reactions (3.1) and (3.2) are parity violating processes, so that the N°'s are produced polarized, leading to a characteristic decay angular distribution. If N° is very massive, it is most favorably studied through its leptonic decay. The chain $e^+e^- \to \bar{\nu}N^\circ$, $N^\circ \to e\mu\nu$ has recently been studied by the authors of Ref. 27, who show how the $e\mu$ collinearity angle distribution allows distinction from charged heavy lepton decay.

We shall here study the $\ell\pi$ decay of the polarized N° produced in e^+e^- annihilation. We first derive the cross section for production of arbitrarily polarized N°; combining with the decay process,[24,28] we find the angular distribution in the N° rest frame, and the center of mass (cms) energy distribution, of the decay

lepton. We work in the framework of model (2.1) and, as in Section III, will make comparisons with a left-handed N°-ℓ coupling normalized to equal strength.

A. Single N°-Production

We have seen that the most accessible reaction for neutral heavy lepton production is $e^+e^- \to \bar{\nu}N^\circ$; we therefore concentrate first on the dynamical characteristics of this production mode.

1. Decay Angular Distribution

Since the distribution of the N° decay products depends on the heavy lepton polarization, we begin by considering the production of N° with spin vector $\hat{s}$ in its rest frame. We choose the y axis in the direction of the incident unpolarized beam. The production process is azimuthally symmetric; we take the zy plane as the reaction plane. With the couplings fixed by Eq. (2.3), the production matrix element is

$$\mathcal{M} = -i \frac{G_F}{\sqrt{2}} M_W^2 \cos\Phi \; \bar{v}_e \gamma_\mu (1-\gamma_5) v_\nu \mathcal{P}_W^{\mu\nu} \; \bar{u}_{N^\circ} \gamma_\nu (1+\lambda\gamma_5) u_e \quad . \tag{5.1}$$

Averaging over the electron and positron spins,

$$\sum_{\text{spins}} |\mathcal{M}|^2 \propto (1+\lambda)^2 \left[m_{N^\circ} p\cdot q \; k\cdot s + k\cdot r \; p\cdot q \right] - (1-\lambda)^2 \left[m_{N^\circ} k\cdot q \; p\cdot s - p\cdot r \; k\cdot q \right] \tag{5.2}$$

where s_μ reduces to $(0, \hat{s})$ in the N° rest frame. The cms angular distribution of the heavy lepton is then

$$\frac{d\sigma_\lambda(\hat{s})}{d\cos\theta_{N^\circ}} = \frac{G_F^2 \, s \cos^2\Phi \, \xi_-^2}{64\pi \left(1 - t/M_W^2\right)^2} \left[A + B\hat{s}_y + C\hat{s}_z \right] \tag{5.3}$$

where

$$A = 4(1+\lambda) + (1-\lambda)(1+\cos\theta_{N^\circ})(\xi_+ + \xi_- \cos\theta_{N^\circ})$$

$$B = -\frac{2m_{N^\circ}}{\sqrt{s}}(1-\lambda)\sin\theta_{N^\circ}(1+\cos\theta_{N^\circ})$$

$$C = 4(1+\lambda) - (1-\lambda)(1+\cos\theta_{N^\circ})(\xi_- + \xi_+\cos\theta_{N^\circ})$$

and

$$\xi_\pm = 1 \pm m_{N^\circ}^2/s \quad . \tag{5.4}$$

To find the angular distribution of the decay electron in the N° rest frame, we make the narrow width approximation and fold (5.3) with the rest frame decay distribution of the polarized heavy lepton. The matrix element for $N^\circ \to e\pi$ decay is

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} m_{N^\circ} f_\pi \cos\Phi \; \bar{u}_e(1-\lambda\gamma_5)\, u_{N^\circ} \quad . \tag{5.5}$$

Hence the electron angular distribution in the N° rest frame is, in the approximation $m_\pi^2 \ll m_{N^\circ}^2$,

$$\frac{d\Gamma}{d\Omega_e} = \frac{G_F^2 f_\pi^2 m_{N^\circ}^3 \cos^2\Phi}{64\pi^2}(1+\lambda\hat{s}\cdot\vec{p}_e) \quad . \tag{5.6}$$

According to Eq. (5.6), the electron is preferentially emitted in the direction of the polarization of N° if the e-N° coupling is right-handed and opposite in the left-handed case. This is easily understood: e and π emerge in opposite directions. Since the electron has $\pm$ helicity for V$\pm$A coupling, it prefers to be emitted along $\hat{s}$ in the former case and opposite in the latter.

For a fixed scattering angle θ_{N°, Eq. (5.3) gives the components of $\hat{s}$ in the N° rest frame. Folding with the distribution (5.6) gives $d\sigma/d\cos\theta_{N^\circ}d\Omega_e$; integrating over θ_{N°, we find

$$\frac{1}{\sigma_\lambda}\frac{d\sigma_\lambda}{d\Omega_e}(e^+e^- \to \bar{\nu}N^\circ_{\hookrightarrow e\pi}) = \frac{1}{4\pi}\left(1+\frac{\lambda B'}{A'}\sin\vartheta\sin\phi + \frac{\lambda C'}{A'}\cos\vartheta\right) \tag{5.7}$$

in terms of the angular coordinates ϑ, ϕ of the decay electron, as defined in Fig. 5, and

$$A' = \int \frac{d\cos\theta_{N^\circ}}{\left(1 - t/M_W^2\right)^2} A \quad . \tag{5.8}$$

B' and C' are defined similarly. The ϕ dependence disappears for V-A coupling and in any case is suppressed at high s. According to Eq. (5.3), N° is at high energies produced preferentially polarized along its flight direction if the e-N° coupling is right-handed or opposite if the coupling is left-handed. In both cases the decay electron prefers to emerge in a direction close to that of its parent.

2. Energy Distribution

The energy distribution of the produced electron in the center of mass system may be similarly derived. The cms decay distribution is

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 m_{N^\circ}^4 \cos^2\Phi f_\pi^2}{16\pi(E_+ + E_-)(E_+ - E_-)^2} \left[E_+ - E_- + \lambda \hat{s}_z (2E_e - E_+ - E_-)\right] . \tag{5.9}$$

$E_\pm$ are the kinematical limits $E_- \leq E_e \leq E_+$:

$$E_+ = \sqrt{s}/2 \ , \qquad E_- = m_{N^\circ}^2/2\sqrt{s} \quad . \tag{5.10}$$

Folding with the production cross section gives

$$\frac{1}{\sigma_\lambda} \cdot \frac{d\sigma_\lambda}{dE_e} = \frac{1}{(E_+ - E_-)^2} \left[E_+ - E_- + \frac{\lambda C'}{A'} (2E_e - E_+ - E_-)\right] \quad . \tag{5.11}$$

The distribution (5.11) is shown in Fig. 6 for m_{N°=1 GeV and $\sqrt{s}$=7 GeV. The difference in slopes is a reflection of the ratio of N° production cross sections for right- (left-) handed couplings. Thus the mean electron energy

$$\langle E_e \rangle = \frac{1}{2} \left(E_+ + E_- + \frac{\lambda C'}{3A'} (E_+ - E_-)\right) \tag{5.12}$$

is insensitive to the chirality of the coupling.

B. N° Pair Production

In the Z resonance region, accessible to the proposed large electron-positron ring,[29] pair production through Z exchange becomes the dominant N° production process with a cross section of order 10^{-32} cm^2 on the resonance peak. For completeness, we record here the analogues of Eq. (5.7) and Eq. (5.11). The relevant matrix element is the $M=N^\circ$ case of Eq. (3.5). Averaging over e^+e^- spins and summing over the $\bar{N}^\circ$ spin gives

$$\begin{aligned}\sum_{\text{spins}} |\mathcal{M}|^2 \propto\ & 2m_{N^\circ} ef(g^2-h^2)(q\cdot r\ p\cdot s - p\cdot r\ q\cdot s) \\ & + 2m_{N^\circ}\left[gh(e^2+f^2) - ef(g^2+h^2)\right] q\cdot s\ k\cdot p \\ & + 2m_{N^\circ}\left[gh(e^2+f^2) + ef(g^2+h^2)\right] p\cdot s\ k\cdot q \\ & + m_{N^\circ}^2(e^2+f^2)(g^2-h^2)\, p\cdot q \\ & + \left[(e^2+f^2)(g^2+h^2) - 4efgh\right] q\cdot r\ k\cdot p \\ & + \left[(e^2+f^2)(g^2+h^2) + 4efgh\right] p\cdot r\ k\cdot q \quad . \end{aligned} \tag{5.13}$$

Then

$$\frac{d\sigma}{d\cos\theta_{N^\circ}}(e^+e^-\to\bar{N}^\circ N^\circ) = \frac{1}{2}\left(\frac{d\sigma}{d\cos\theta_{N^\circ}}\right)_{\text{unpol}} + \hat{s}_z\left(\frac{d\sigma}{d\cos\theta_{N^\circ}}\right)_{\text{pol}} , \tag{5.14}$$

where $(d\sigma/d\cos\theta_{N^\circ})_{\text{unpol}}$ is given by Eq. (3.7) and, with $m_{N^\circ}^2 \ll s$,

$$\left(\frac{d\sigma}{d\cos\theta_{N^\circ}}\right)_{\text{pol}} = \frac{1}{32\pi}\frac{s}{\left(s-M_Z^2\right)^2+\Gamma_Z^2 M_Z^2}\left\{gh(e^2+f^2)\left(1+\cos^2\theta_{N^\circ}\right) + 2ef(g^2+h^2)\cos\theta_{N^\circ}\right\}. \tag{5.15}$$

We have neglected the dependence on $\hat{s}_y$ and hence on the azimuthal angle ϕ, which disappears as $m_{N^\circ}^2 \ll s$.

1. Decay Angular Distribution

Combining with the $\ell\pi$ decay, we find the N° rest frame electron distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_e}(e^+e^- \to \bar{N}^\circ N^\circ_{\hookrightarrow e\pi}) = \frac{1}{4\pi}\left(1+\frac{2\,gh}{g^2+h^2}\cos\vartheta\right) \quad . \tag{5.16}$$

The asymmetry vanishes if the heavy lepton neutral current is purely vector or axial vector (g=0 or h=0). With the couplings of model (2.1) the distribution shows maximum asymmetry

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_e} = \frac{1}{4\pi}\ (1+\cos\vartheta) \quad . \tag{5.17}$$

2. Energy Distribution

The cms electron energy distribution is

$$\frac{1}{\sigma}\frac{d\sigma}{dE_e}(e^+e^- \to \bar{N}^\circ N^\circ_{\hookrightarrow e\pi}) = \frac{1}{(E_+-E_-)^2}\left[E_+-E_- + \frac{2\lambda gh}{g^2+h^2}(2E_e-E_+-E_-)\right] \tag{5.18}$$

within the kinematical limits $E_\pm = \frac{\sqrt{s}}{4}(1\pm\beta)$, $\beta=\sqrt{1-4m^2_{N^\circ}/s}$. It follows from the decay distribution (5.9) that (5.18) is linear in E_e, as in the case of single-N° production. With g=0 or h=0, (5.18) is flat, reflecting the isotropy of the rest frame angular distribution. Model (2.1) couplings give

$$\frac{1}{\sigma}\frac{d\sigma}{dE_e} = \frac{2}{(E_+-E_-)^2}\ (E_e-E_-) \quad . \tag{5.19}$$

VI. DISCUSSION

Electron-positron colliding beams offer the most accessible means for production of the neutral heavy leptons expected in most modern gauge models of the weak interactions. Right-handed N°'s may be produced singly and in pairs through the reactions $e^+e^- \to \bar{\nu}N^\circ$, $e^+e^- \to \bar{N}^\circ N^\circ$. At the top energy range of machines now under construction, the total heavy lepton production cross section is of order 10^{-35} cm^2, as compared to the $e^+e^- \to \mu^+\mu^-$ cross section, of order

10^{-34} cm^2. N° may be detected through its leptonic decay $N^\circ \to \mu e \nu$ or, if not very massive, through the two body channel $N^\circ \to \ell\pi$. In the former case, it is necessary to distinguish the signal from the numerically comparable $e\mu$ signal of an electromagnetically produced pair of charged heavy leptons. This may be done[27] on the basis of the $e\mu$ collinearity angle. The e and μ produced by N° decay follow the parent's direction, so that $d\sigma/d\cos\theta_{e\mu}$ is peaked near $\cos\theta_{e\mu} = -1$.[30] In contrast, if e and μ are products of charged heavy lepton decay: $e^+e^- \to U^+U^- \to \mu e + \nu$'s, they tend to emerge in opposite directions, with peaking near $\cos\theta_{e\mu} = +1$. The $e\mu$ invariant mass and energy distributions distinguish the chirality of the ℓ-N° coupling.

In this paper we have studied the production of neutral heavy leptons in e^+e^- annihilation and discussed the characteristics of their subsequent decay into the $\ell\pi$ channel. We derived the angular distributions of singly and pair-produced N°'s and showed how these characterized the nature of the heavy lepton coupling. In particular, in single N° production, right-handed ℓ-N° coupling yields a near-isotropic distribution in $\cos\theta_{N^\circ}$, while a left-handed N° emerges preferentially in the forward direction. The angular distribution of the heavy lepton may be inferred by the detection of its decay products.

Examination of the decay electron distributions shows characteristic features. A V±A e-N° coupling is reflected in the asymmetry of the electron angular distribution in the N° rest frame. A parity conserving heavy lepton neutral current produces an isotropic distribution in the energy region where Z exchange dominates. Single N° production dominates off the Z peak. With the results of Sections III and IV, we estimate for $\sqrt{s}/2 = 4$ GeV, $\sigma(e^+e^- \to \bar{\nu} N^\circ_{\hookrightarrow \ell\pi}) = 2.0 \times 10^{-37}$ cm^2 for $m_{N^\circ_1} = 1.0$ GeV and $m_{N^\circ_2} = 2.4$ GeV. With SPEAR/DORIS luminosity, this means a rate of 0.2 events per day. In the PEP/PETRA range

$\sqrt{s}/2 = 16$ GeV, $\sigma = 2.7 \times 10^{-36}$ cm^2 or 23 events/day. The rate may be an order of magnitude smaller if N_1° is as heavy as 5 GeV. Left-handed neutral heavy leptons of model (2.5) are pair produced at a rate which becomes appreciable in the region of the Z resonance. If N_U° is heavier than its charged partner U^-, the sequence of production and decay is $e^+e^- \xrightarrow{Z} \bar{N}_U^\circ N_U^\circ$, $N_U^\circ \to U\ell\nu$. U may then decay leptonically, giving the signature $e^+e^- \to \ell^+\ell^-\ell^+\ell^- + \nu$'s. Since U can only decay through neutral particle mixing, it is expected to have an anomalously long lifetime,[27] $\tau \geq 10^{-11}$ sec, possibly being directly detectable.

In view of the important role played by neutral heavy leptons in contemporary gauge models of the weak interactions, we look forward to their detection and study at the electron-positron storage ring PEP and PETRA at present under construction.

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TABLE I

Production rate of neutral heavy leptons at representative SPEAR/DORIS and PEP/PETRA energies.

	Coupling	Events/Day	Percentage Pair-Produced
$\sqrt{s}/2 = 4$ GeV	V+A	0.9	8%
(SPEAR/DORIS)	V-A	0.3	25%
$\sqrt{s}/2 = 16$ GeV	V+A	121	13%
(PEP/PETRA)	V-A	42	38%

FIGURE CAPTIONS

1. (a) Feynman diagram for the reaction $e^+e^- \to \bar{\nu}N^\circ$. (b) Feynman diagrams for the reaction $e^+e^- \to \bar{N}^\circ N^\circ$.
2. Integrated cross sections for the reactions $e^+e^- \to \bar{\nu}N_1^\circ$ and $e^+e^- \to \bar{N}_1^\circ N_1^\circ$, computed from Eqs. (3.9) and (3.10) with $\Phi = \pi/4$.
3. Total width of N° as a function of m_{N°.
4. Branching ratios for the decays $N^\circ \to e(\mu) + \ldots$ as a function of m_{N°.
5. The decay $N^\circ \to e(\mu)\pi$ in the heavy lepton rest frame. The initial e^- and e^+ define the z-y plane and the positive z-axis is opposite the direction of the produced antineutrino.
6. Energy distribution for the reaction $e^+e^- \to \bar{\nu}N^\circ$ ($\hookrightarrow e\pi$) with different chirality: $\lambda = \pm 1$.

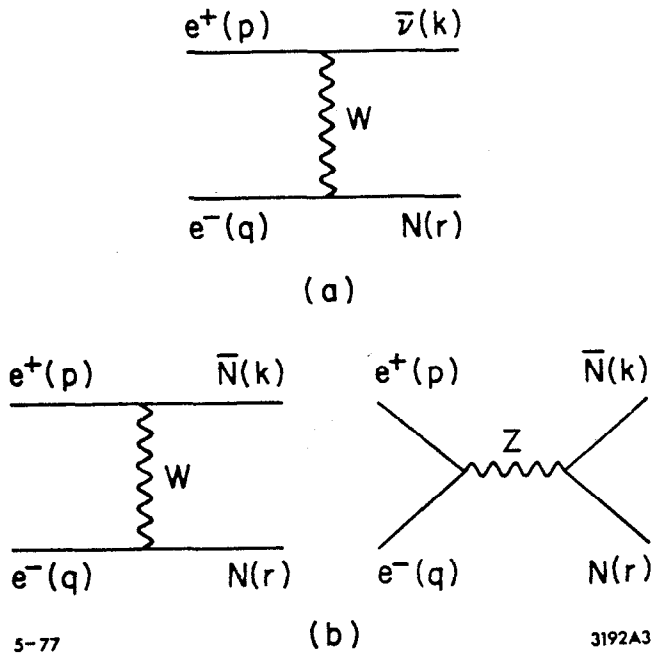

Fig. 1

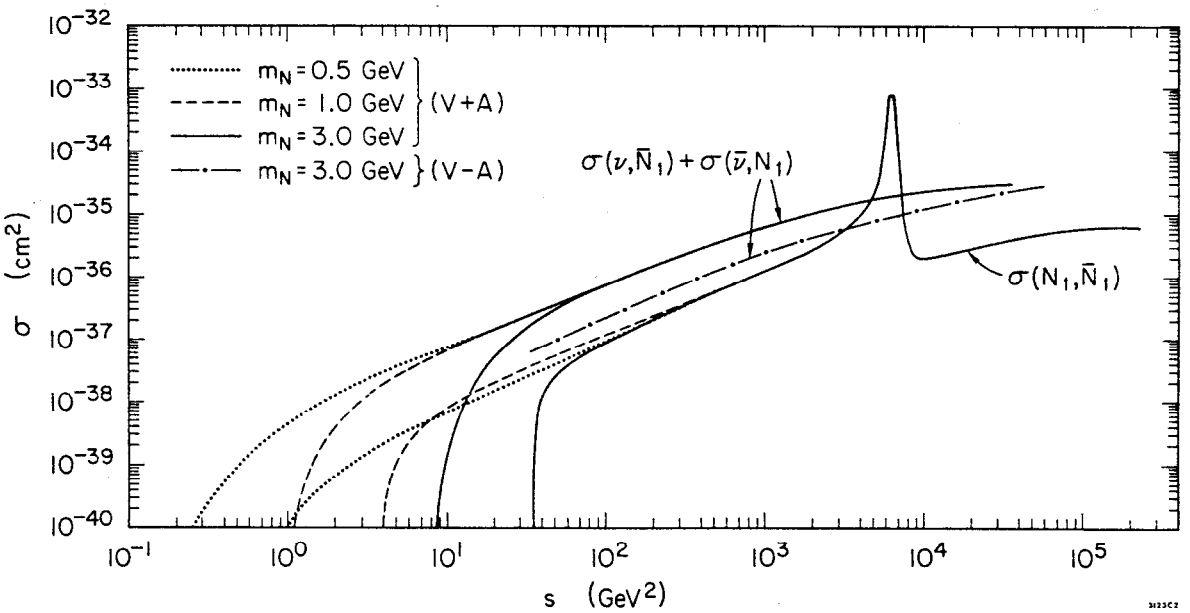
$m_N = 0.5$ GeV
$m_N = 1.0$ GeV
$m_N = 3.0$ GeV
(V+A)
$m_N = 3.0$ GeV
(V−A)
$\sigma(\nu,\bar{N}_1) + \sigma(\bar{\nu},N_1)$
$\sigma(N_1,\bar{N}_1)$
σ (cm^2)
s (GeV^2)
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

Fig. 2

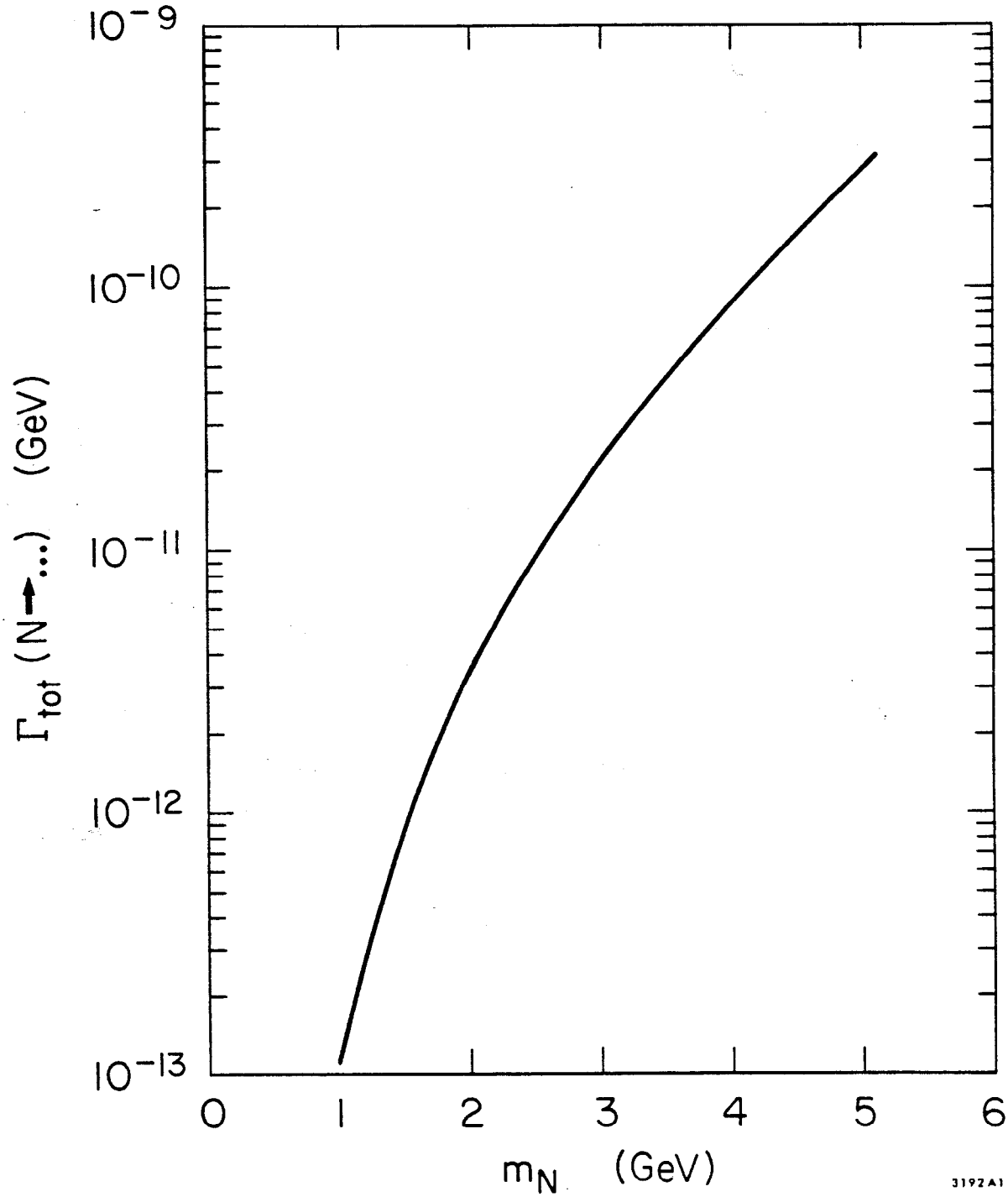

Fig. 3

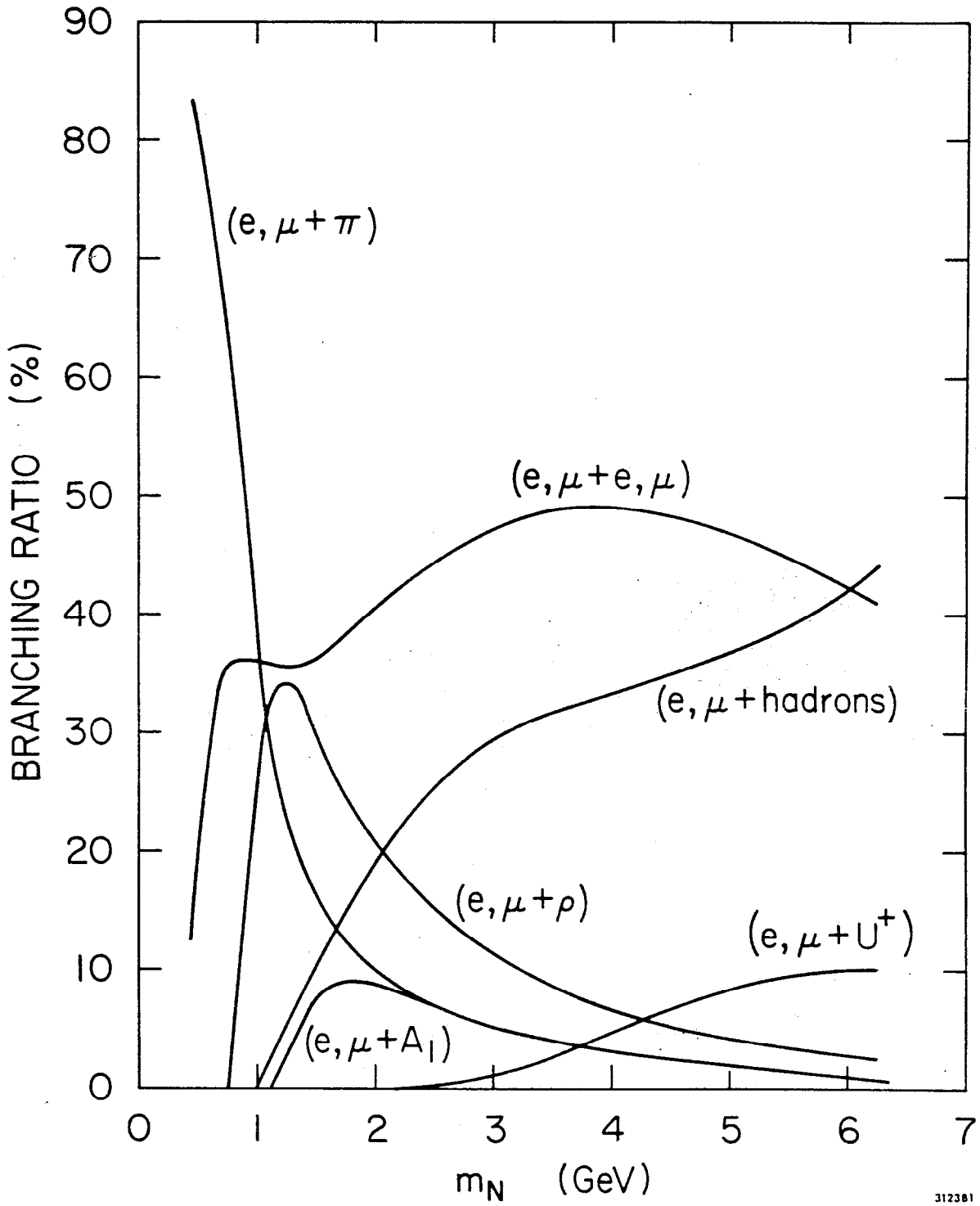
90
80
70
60
50
40
30
20
10
0
BRANCHING RATIO (%)
(e, μ+π)
(e, μ+e, μ)
(e, μ+hadrons)
(e, μ+ρ)
(e, μ+U+)
(e, μ+A1)
0
1
2
3
4
5
6
7
mN (GeV)
312381

Fig. 4

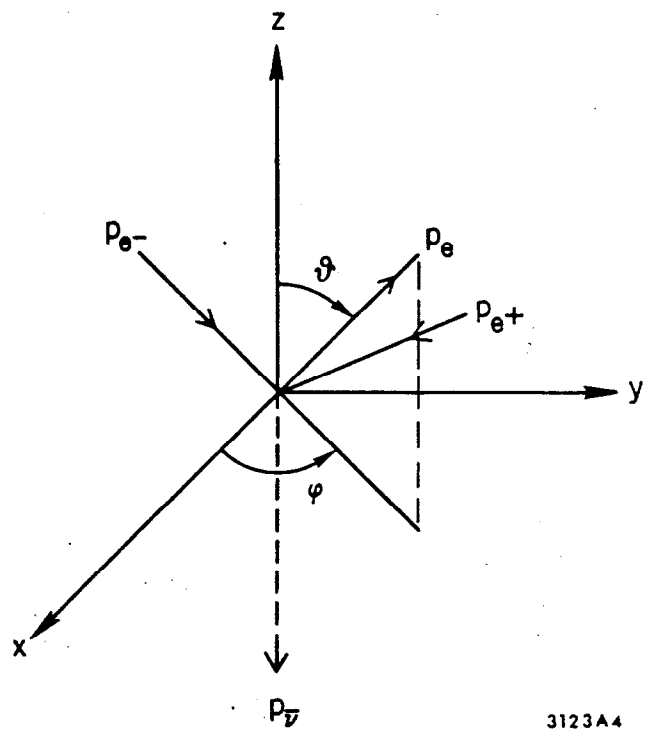

Fig. 5

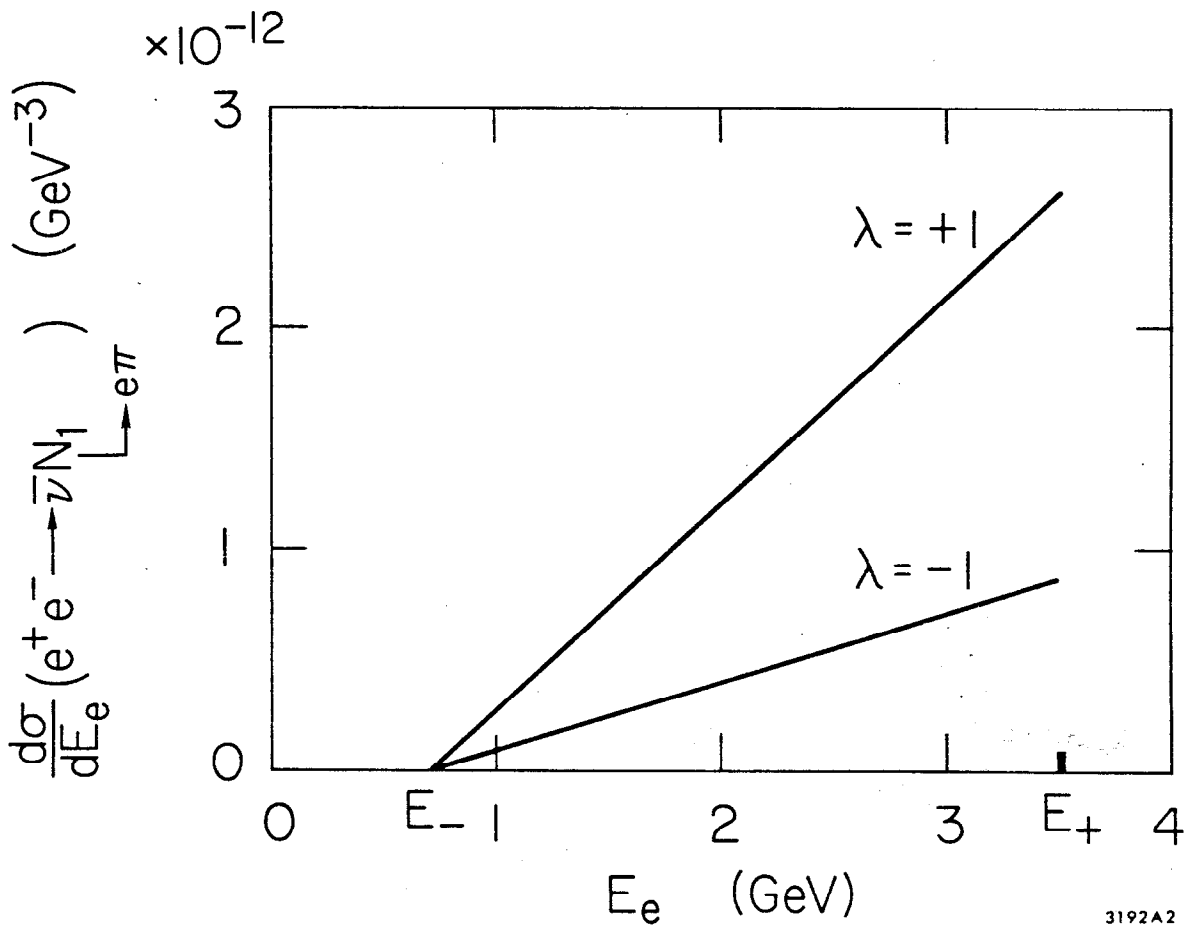

Fig. 6