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# RIGHT-HANDED NEUTRAL HEAVY LEPTONS IN $e^+e^-$ ANNIHILATION?*

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## ABSTRACT

The experimental implications of neutral heavy leptons N in $e^+e^-$ annihilation are examined. We calculate the production rate of both right-handed and left-handed N's at SPEAR and PEP/PETRA energies and show that observation of the process $e^+e^- \to \bar{\nu}N$, $N \to e$ (or $\mu$)$\pi$ allows the determination of both the mass and handedness of N.

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Considerable interest has recently been shown [1-6] in the possible enlargement of the leptonic world to encompass right-handed neutral heavy leptons. In such schemes, neutral leptons E and M, forming right-handed doublets

$$\begin{pmatrix} E \\ e \end{pmatrix}_R \qquad \begin{pmatrix} M \\ \mu \end{pmatrix}_R \tag{1}$$

are added to the original Weinberg-Salam (W-S) model [7]. Here

$$\begin{aligned} E &= \cos\phi\, N_e + \sin\phi\, N_\mu \\ M &= -\sin\phi\, N_e + \cos\phi\, N_\mu \quad , \end{aligned} \tag{2}$$

$N_e$ and $N_\mu$ are mass eigenstates, and $\phi$ is an undetermined mixing angle. The neutrino neutral current is as in the W-S model; however it follows immediately from the assignment (1) that the electronic and muonic neutral currents are purely vector. Consequently, parity-violating effects in atoms are suppressed, a desirable feature if the measurements of the optical rotation in bismuth by the Oxford and Washington groups [8] remain at their present value. Further, the mixing scheme (2) implies the existence of lepton number nonconserving processes such as $\mu \to e + \gamma$ for which the current limit [9] on the branching ratio is $2.2 \times 10^{-8}$. This may be just an order of magnitude above the value predicted by the model (1) [10]. The N's are expected to decay into a pair of conventional leptons (plus a neutrino), a lepton and hadrons such as $\pi$, $\rho$, $A_1$, and, if sufficiently massive, into a conventional lepton plus a heavy charged lepton. They may be produced in deep inelastic $\mu p$ and ep experiments and would be expected to appear in the decay products of charmed mesons D, D*, F, F*.

In this letter we examine the experimental implications of such leptons in $e^+e^-$ annihilation. We address ourselves to the question how and where they can

be found and what theoretical information can be extracted from the data.

We begin our discussion with N production and distinguish between the reactions $e^+e^- \to \bar{\nu}N_e$ ($\nu\bar{N}_e$) and $e^+e^- \to N_e\bar{N}_e$. The former occurs through W-exchange whereas the latter receives contributions from W- and Z-exchange diagrams.

The distributions in the center-of-mass scattering angle $\theta_N$ for single and pair production of $N_e$-leptons are

$$\frac{d\sigma}{d\cos\theta_N}(e^+e^- \to \bar{\nu}N_e) = \frac{G_F^2 s\cos^2\phi(1-m_N^2/s)^2}{32\pi(1-t/M_W^2)^2}\Big\{2(1+\lambda)(1-m_N^2/s)+(3+\lambda)(1+m_N^2/s)$$

$$+ 2(1-\lambda)\cos\theta_N + (1-\lambda)(1-m_N^2/s)\cos^2\theta_N\Big\} \tag{3a}$$

$$\equiv \cos^2\phi\,\frac{d\hat{\sigma}}{d\cos\theta_N}$$

$$\frac{d\sigma}{d\cos\theta_N}(e^+e^- \to N_e\bar{N}_e) = \frac{G_F^2\delta s}{16\pi}\Big\{\cos^4\phi\,\frac{(1+\delta\cos\theta_N)^2}{(1-t/M_W^2)^2}+\frac{1}{2}\frac{\cos^2 2\theta_W(1+\delta^2\cos^2\theta_N)}{(1-s/M_Z^2)^2+\Gamma_Z^2/M_Z^2}$$

$$+\frac{\cos 2\theta_W\cos^2\phi\;(1+\delta\cos\theta_N)^2(1-s/M_Z^2)}{(1-t/M_W^2)[(1-s/M_Z^2)^2+\Gamma_Z^2/M_Z^2]}\Big\} \tag{3b}$$

$$\equiv \cos^4\phi\,\frac{d\hat{\sigma}_W}{d\cos\theta_N}+\frac{d\hat{\sigma}_Z}{d\cos\theta_N}+\cos^2\phi\,\frac{d\hat{\sigma}_{int}}{d\cos\theta_N}\ .$$

s is the center-of-mass energy squared, t is the momentum transfer squared, $\Gamma_Z$ is the width of the neutral intermediate vector boson, and $\delta \equiv (1-4m_N^2/s)^{\frac{1}{2}}$. The phenomenological possibility of a left-handed N has been allowed for by the introduction of the parameter $\lambda = \pm 1$ for $V \pm A$ e-$N_e$ coupling. In the case of $N_\mu$-production, $\cos\phi$ is replaced by $\sin\phi$.

For right-handed coupling, the distribution (3a) is isotropic as expected from angular momentum considerations [11]. The V-A case shows a characteristic $(1+\cos\theta_N)^2$ behaviour in the region $s \gg m_N^2$: a left-handed heavy lepton is produced preferentially in the forward direction.

Eqs. (3a) and (3b), integrated over $\theta$, are plotted in fig. 1 as functions of s [12]. Single N-production outweighs N-pair production by one order of magnitude outside the Z-resonance region; N-pair production obviously dominates around the Z. Changing V+A to V-A does not affect $\sigma(N_e, \bar{N}_e)$, whereas the single-N channel is reduced by a factor 2-3. When $(m_{N_\mu}^2 - m_{N_e}^2) \ll s$, the total heavy lepton production cross section becomes independent of the mixing angle and is

$$\begin{aligned}\sigma_{tot} &= \sum_{i=e,\mu} \sigma(e^+e^- \to \bar{\nu} N_i) + \sigma(e^+e^- \to \nu \bar{N}_i) + \sum_{i,j} \sigma(e^+e^- \to N_i \bar{N}_j) \\ &= 2(\hat{\sigma} + \hat{\sigma}_Z) + \hat{\sigma}_W + \hat{\sigma}_{int}\end{aligned} \tag{4}$$

From eqs. (3a), (3b), and (4) we find that, for a PEP/PETRA energy of $\sqrt{s}/2 = 16$ and a projected luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, the production rate of right-handed N's is 128/day, of which 20% are pair-produced. The corresponding results for the V-A case and the rate at maximum SPEAR energy $\sqrt{s}/2 = 4$ and luminosity $10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ are shown in table 1.

A particularly clean reaction for the detection and the study of N-leptons and their dynamical behaviour is the chain

$$e^+e^- \to \bar{\nu} N, \quad N \to e(\text{or } \mu) + \pi \tag{5}$$

as has been emphasized by Bjorken [13]. The N-momentum can be reconstructed from events with only a charged pion and lepton in the final state, allowing determination of the heavy lepton mass. Furthermore, the differential distributions of the final state products depend sensitively on the handedness of

the N-e ($\mu$) coupling. The N's are produced polarized, leading to a characteristic decay angular distribution in the N-rest frame.

The counting rates for this reaction depend on the branching ratios for N decay; these have been calculated following refs. [14] and [15]. For $m_\mu/m_N \ll 1$, they are independent of the mixing angle $\phi$. Our results are shown in fig. 2 [16]. The e ($\mu$) $\pi$ mode is dominant for $m_N \lesssim 1$ GeV, dropping rapidly to 5% at $m_N = 3$GeV. As an example, let us assume right-handed $N_e$ and $N_\mu$ of masses 1.0 and 2.4 GeV. Then the cross section for reaction (5) is $2.0\times10^{-37}$ cm$^2$ and $2.7\times10^{-36}$ cm$^2$ at $\sqrt{s}/2=4$ and 16 GeV respectively. This means 0.2 and 23 events per day; in the V-A case the corresponding numbers are reduced by a factor 4. The rate may be an order of magnitude smaller if $N_e$ is as heavy as 5 GeV.

The electron decay angular distribution in the N-rest frame (see fig. 3) is

$$\frac{d\sigma}{d\Omega}(e^+e^- \to \bar{\nu} N_e \hookrightarrow e\pi) = \frac{G_F^4 f_\pi^2 m_N^3 \cos^4\phi}{2^{11}\Gamma_N \pi^3}(1-m_\pi^2/m_N^2)^2(1-m_N^2/s)^2 \int_{-1}^{1} \frac{d\cos\theta_N}{(1-t/M_W^2)^2}$$

$$\Big\{4s(1+\lambda)(1+\lambda\cos\vartheta)+(1-\lambda)(1+\cos\theta_N)[s+m_N^2+(s-m_N^2)\cos\theta_N \tag{6}$$

$$-\lambda\cos\vartheta(s-m_N^2+(s+m_N^2)\cos\theta_N)]+2m_N\sqrt{s}(1-\lambda)\sin\theta_N(1+\cos\theta_N)\sin\vartheta\sin\varphi\Big\}$$

where $f_\pi$ is the pion decay constant. The dependence on the azimuthal angle disappears for V-A coupling and in any case is suppressed at high s. In the high energy regime, the N is preferentially polarized along its flight direction if its coupling to the familiar leptons 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.

The characteristics of the center-of-mass distributions of the final state electron are:

(i) $d\sigma/dE_e$ grows roughly linearly within the kinematical limits $E_e^{min} = \frac{m_N^2 - m_\pi^2}{2\sqrt{s}}$, $E_e^{max} = \frac{m_N^2 - m_\pi^2}{2m_N^2}\sqrt{s}$.

(ii) The slope of the curve for (V+A) e-N coupling is substantially bigger than for V-A coupling.

(iii) The average electron energy $\langle E_e \rangle \simeq 3.0$ (11.0) GeV for $\sqrt{s} = 7.0$ (30.0) GeV grows linearly with $\sqrt{s}$.

(iv) $d\sigma/d\cos\theta_e$ is represented in fig. 4. One notices a near isotropic angular distribution for (V+A) coupling whereas a (V-A) coupling leads to an angular distribution which is strongly suppressed in the backward hemisphere.

These characteristics reflect the behaviour of $d\sigma/d\cos\theta_N$ as given in eq. (3a).

Our investigation shows that neutral right-handed heavy leptons, if they exist, should be detectable at PEP/PETRA energies and their dynamical characteristics can be determined in several ways by the experiment.

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[10] For example with the choice $\phi = \pi/4$, $m_{N_e} = 1$ GeV, $m_{N_\mu} = 2.4$ GeV, $\Gamma_{\mu e\gamma}/\Gamma \sim 10^{-9}$.

[11] There is some suppression in the backward direction due to the effect of the intermediate vector boson propagator.

[12] Here we have assumed for definiteness a mixing angle $\phi = \pi/4$ and take the Weinberg angle to be $\sin^2\theta_W = 0.35$.

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Table 1

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

| | Coupling | Events/day | Percentage Pair-produced |
|---|---|---|---|
| $\frac{\sqrt{s}}{2} = 4$ GeV (SPEAR) | V+A | 0.9 | 12% |
| | V-A | 0.4 | 41% |
| $\frac{\sqrt{s}}{2} = 16$ GeV (PEP/PETRA) | V+A | 128 | 20% |
| | V-A | 50 | 48% |

Figure Captions

1. The total cross section for the processes $e^+e^- \to \bar{\nu}N_e$ and $e^+e^- \to N_e\bar{N}_e$, computed from eqs. (3a) and (3b), with $\phi = \pi/4$ and $\sin^2\theta_W = 0.35$.

2. Branching ratios for the decays $N \to e^-$ (or $\mu$) + ... as a function of $m_N$.

3. The decay $N \to e\,(\mu)\pi$ 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.

4. Distribution of the decay electron of reaction (5) in the center-of-mass frame for (V±A) coupling with $m_N = 1$ GeV and $\sqrt{s} = 30$ GeV.

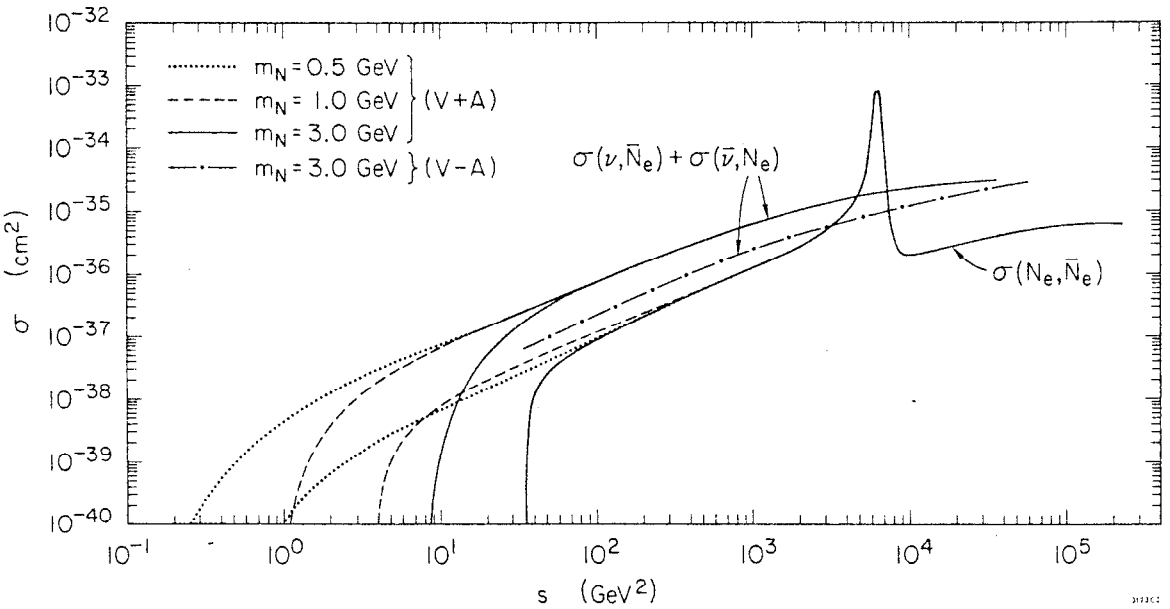
$m_N = 0.5$ GeV
$m_N = 1.0$ GeV
$m_N = 3.0$ GeV
(V+A)
$m_N = 3.0$ GeV
(V−A)
$\sigma(\nu,\bar{N}_e) + \sigma(\bar{\nu},N_e)$
$\sigma(N_e,\bar{N}_e)$
$\sigma$ (cm$^2$)
s (GeV$^2$)
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^{-36}$
$10^{-37}$
$10^{-38}$
$10^{-39}$
$10^{-40}$
$10^{-1}$
$10^{0}$
$10^{1}$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

Fig. 1

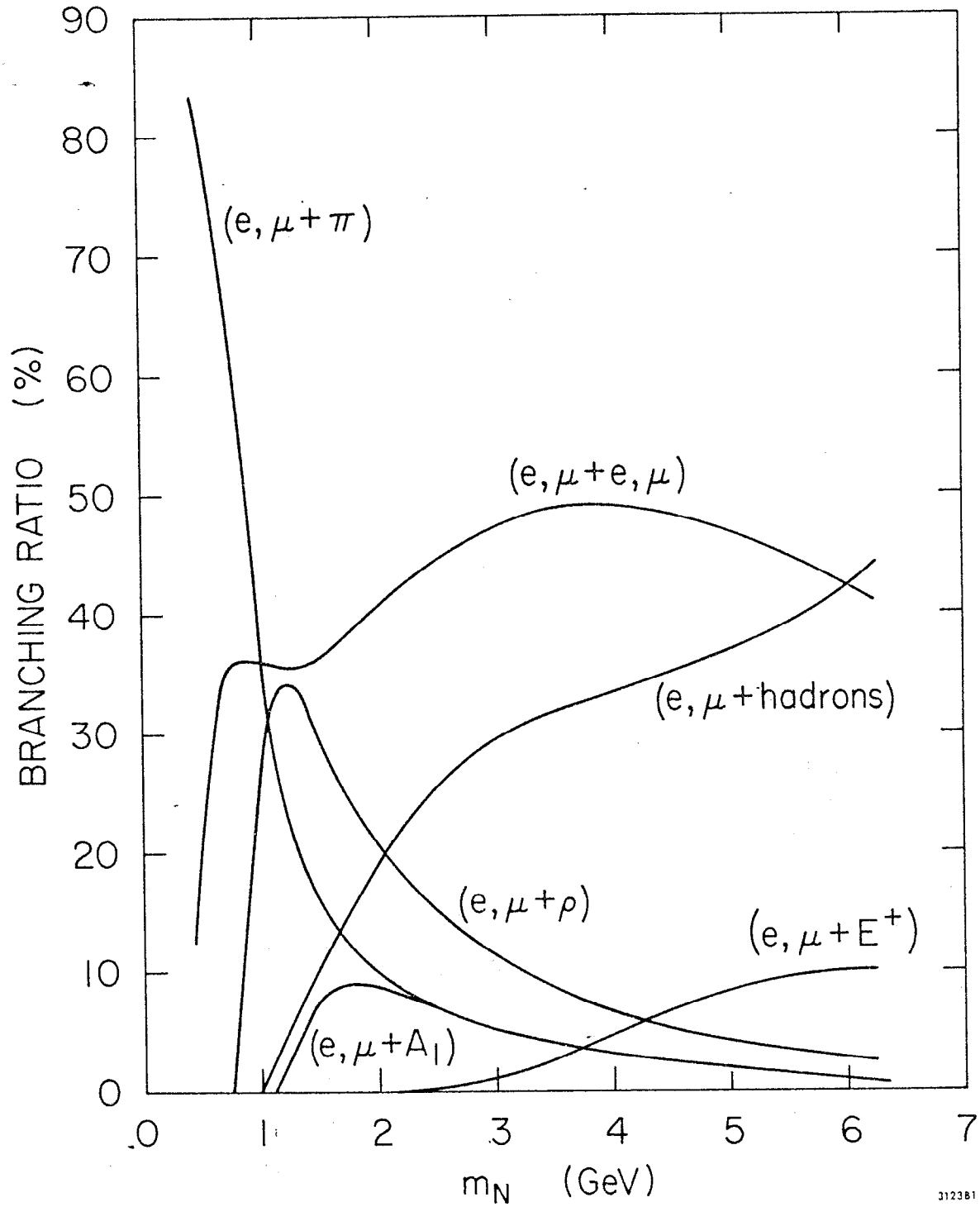
90
80
70
60
50
40
30
20
10
0
BRANCHING RATIO (%)
(e, μ+π)
(e, μ+e, μ)
(e, μ+hadrons)
(e, μ+ρ)
(e, μ+E+)
(e, μ+A1)
0
1
2
3
4
5
6
7
mN (GeV)
3123B1

Fig. 2

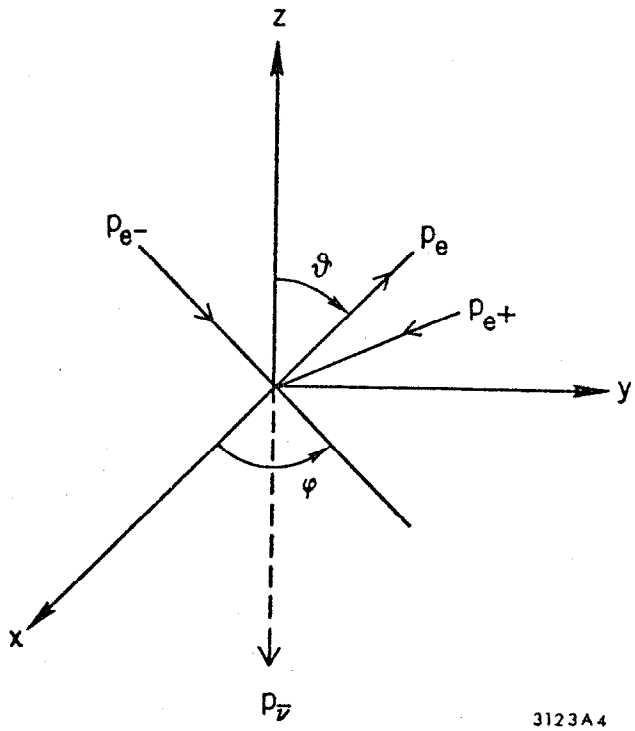


Fig. 3

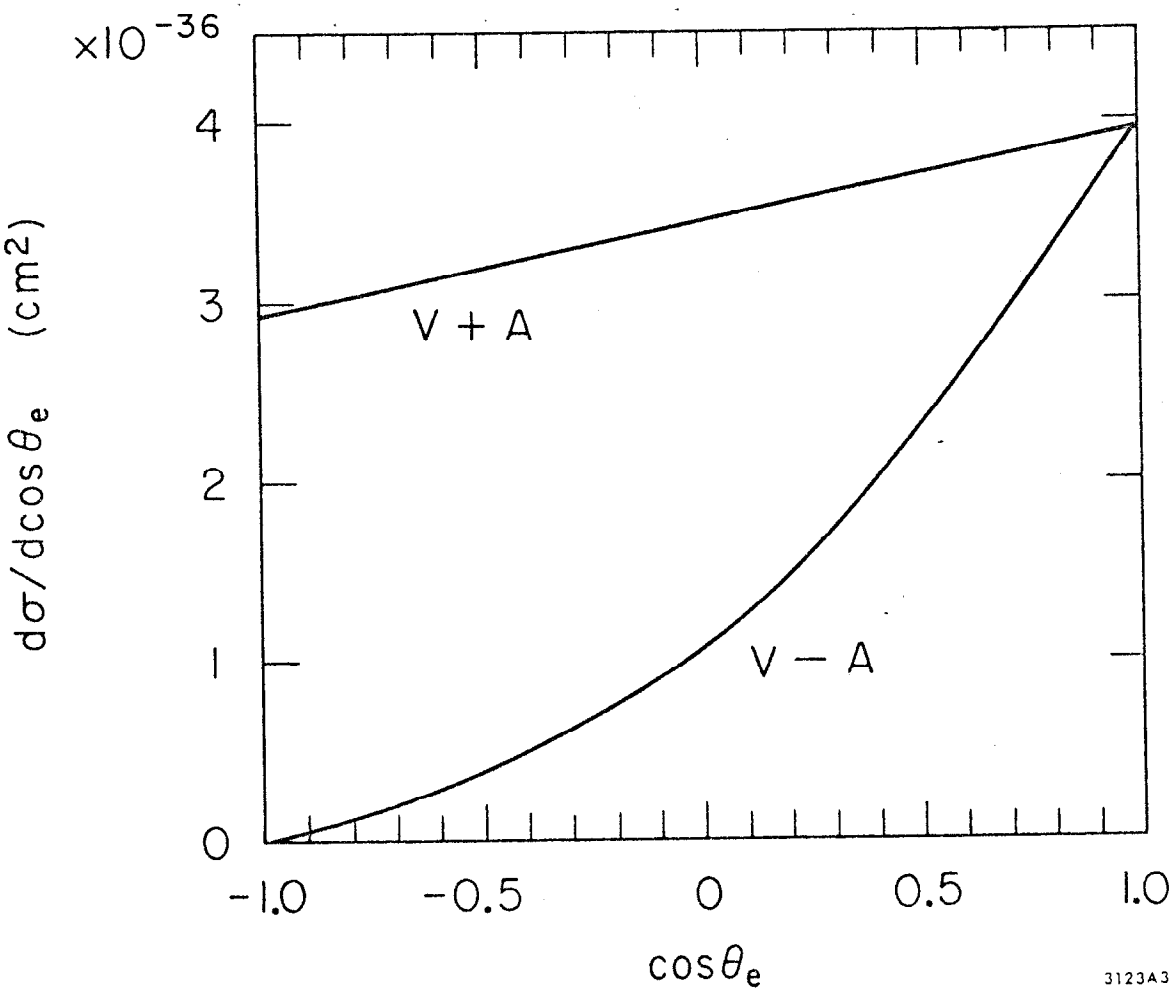


Fig. 4