at High Energies, Hamburg, 1977, edited by F. Gutbrod (DESY, Hamburg, Germany, 1977).

[6]P. Alibran *et al.*, Phys. Lett. 74B, 422 (1978).

[7]To determine the scan efficiency a sample of 134 high-energy forward e^+, e^-, and γ's was used. The overall result of $(78 \pm 15)\%$ is consistent with that of $(86 \pm 20)\%$ obtained from the eleven single-e^- events alone.

[8]In a sample of 27 600 total $\nu_\mu \to \mu^-$ interactions, we found 187 ± 14 and 28 ± 6 total $\nu_e \to e^-$ and $\bar{\nu}_e \to e^+$ interactions, respectively [A. Cnops *et al.*, Phys. Rev. Lett. 40, 144 (1978)]. We scale these numbers by 106 000/27 600 to obtain 723 ± 54 and 108 ± 23 total ν_e and $\bar{\nu}_e$ interactions, respectively, in the present sample. From these numbers we estimate that we should have fifteen $\nu_e n \to e^- p$ and six $\bar{\nu}_e p \to e^+ n$ events, consistent with the actual numbers we see.

[9]This estimate is in good agreement with the measurement by Alibran *et al.* (Ref. 6) of $R_\mu = (\mu^-$ within $3°)$ (proton unseen)$/(\mu^- + p) = (5 \pm 3)\%$, assuming ν_e-ν_μ universality.

[10]The fiducial volume is defined by $R \le 170$ cm, $|z| \le 125$ cm, and $D \ge 78$ cm, where R is the distance from the center of the chamber, z is the vertical distance from the median plane, and D is the distance from the back wall of the chamber along the beam direction.

[11]The 10% loss due to the $E_e \ge 2$ GeV cut was calculated using the Weinberg-Salam model with a $\sin^2\theta_W = \frac{1}{4}$. However, this loss is only weakly dependent on the model used.

[12]K. Schultze, in *Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977,* edited by F. Gutbrod (DESY, Hamburg, Germany, 1977).

[13]M. Holder *et al.*, Phys. Lett. 71B, 222 (1977); B. C. Barish *et al.*, in *Proceedings of the International Neutrino Converence, Aachen, West Germany, 1976,* edited by H. Faissner, H. Reithler, and P. Zerwas (Vieweg, Braunschweig, 1977).

Effects of the Transition Magnetic Moment of the Neutrino

Jihn E. Kim
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 22 May 1978)

It is shown that a sizable transition magnetic moment between ν_μ and a massive neutrino ν' (of mass of approximately 100 MeV) leads to some detectable effects. These effects could be revealed significantly in ν_μ- ($\bar{\nu}_\mu$-) electron scattering, but would remain hidden in most other cases. It is also pointed out under what circumstances a large transition magnetic moment arises in gauge models.

The stringent upper limits on the masses of the known neutrinos (ν_e, ν_μ) appear to imply almost negligible neutrino magnetic moments. In this Letter, however, we wish to explore the possibility that there is actually no fundamental reason for such magnetic moments to be very small.[1-3] Certainly, if the neutrino magnetic moments are larger than the usual estimates, their effects might have been noticed in recent experiments on the muonless events in ν_μ $(\bar{\nu}_\mu)$ interactions. But suppose that there exists a heavy neutrino ν' with a mass of order of 100 MeV and lifetime of 10^{-9} sec,[4] and that this neutrino and, say, ν_μ have a larger transition magnetic moment than is usually expected. Such a ν' will have escaped detection so far, but may show up in the near future.[5]

Let us therefore consider a transition magnetic moment[6] between ν_μ and ν' which interacts via photon exchange with charged particles according to[7]

$$\mathfrak{L}_{\rm int} = -e^2(f'/2m_e)\bar{\nu}'\sigma^{\mu\alpha}q_\alpha(1+\gamma_5)\nu_\mu q^{-2}(-\bar{e}\gamma_\mu e + \tfrac{2}{3}\bar{u}\gamma_\mu u + \ldots), \qquad (1)$$

where $f'/2m_e$ is the transition magnetic moment in question. The interaction in Eq. (1) is very different for different regions of $Q^2 = -q^2$:

(i) At Q^2 so small that $f'|Q|/Q^2 m_e \gg G_F$, it is larger than the neutral-current weak interaction. Therefore, it is important in ν_μ collisions with a light target such as an electron since in this $Q^2 \cong 2m_e E_e'$, where E_e' is the energy of the recoil electron.

(ii) At large Q^2, it becomes negligible. Here, e.g., in the case of $\nu_\mu + p \to \nu' + p$, we have $Q^2 \cong 2m_p E_p'$, where E_p' is the energy of the recoil proton. Hence, ν-hadron scattering is not affected[8] significantly for reasonable values of f'.[6,9]

(iii) If the mass of ν' is of the order of 100 MeV, the effect will not be important in low-energy ν_μ-,

$\bar{\nu}_\mu$-, ν_e-, and $\bar{\nu}_e$-electron scatterings.[10] In fact, the threshold for $\nu_\mu + e \to \nu' + e$ occurs at 10 GeV.

From the above comments, we see that the best way to detect ν' is by means of high-energy ν_μ- and $\bar{\nu}_\mu$-electron scattering. The cross section in this case due to (1) is[11]

$$\frac{d\sigma(\nu_\mu e \to \nu' e)}{dE_e'} = \frac{d\sigma(\bar{\nu}_\mu e \to \bar{\nu}' e)}{dE_e'} = \frac{16\pi\alpha^2}{E_e'}\left(\frac{f'}{2m_e}\right)^2 \theta\left(1 - \frac{m'^2}{2m_e E}\right)\left\{\left(1 - \frac{E_e'}{E}\right) - \frac{1}{2}\left[\frac{m'^2}{m_e E} - \frac{m'^2 E_e'}{2m_e E^2} - \frac{m'^4}{4m_e^2 E^2}\right]\right\}, \tag{2}$$

where E is the incident neutrino energy, E_e' the energy of the recoil electron, and m' the mass of the heavy neutrino ν'. (If we were to account for the reported number of "anomalous" high-energy $\nu_\mu e$ events[5,12] with this mechanism, we would need $f' \approx 3\times 10^{-8}$ for $m' \approx 100$ MeV.)

We proceed to present a model which gives a weak transition magnetic moment of the above type. In such a model we need[6] a right-handed ν' and a massive charged lepton M^- which couples to ν_μ. Thus, in the SU(2)⊗U(1) model[13] [Weinberg-Salam (WS)] we consider the following muonic lepton doublets:

$$\begin{pmatrix} \nu_\mu \cos\varphi - N^0 \sin\varphi \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \sin\varphi + N^0 \cos\varphi \\ M^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu' \\ M^- \end{pmatrix}_R, \tag{3}$$

where φ is a mixing angle and N^0 is assumed to be heavier than 400 MeV. We may or may not also insert $(N^0, \mu)_R$, depending on the outcome of the atomic parity-nonconservation experiments, and electronic lepton doublets can be treated symmetrically in such a way as to maintain electron-muon universality (note, however, that this is an artificial scheme). Then, the transition magnetic moment between ν_μ and ν' is[6]

$$f' - \frac{G_F m_e m_{M^-}}{4\sqrt{2}\pi^2}\,\frac{\sin\varphi}{\cos^2\varphi}\left[1 + \frac{3}{1-y} + \frac{3y\ln y}{(1-y)^2}\right], \tag{4}$$

where $y = m_{M^-}^2/M_W^2$, $g^2\cos^2\varphi/8M_W^2 = G_F/\sqrt{2}$, and typical diagrams are shown in Fig. 1. Quark-lepton universality will be satisfied if we introduce quark doublets $([u\cos\theta_C - c\sin\theta_C]\cos\varphi - t\sin\varphi, d)_L$, etc.[14] Assuming $\sin\varphi/\cos^2\varphi \approx 1$, we have, for small values of y, $f' \approx 4.2\times 10^{-10} m_{M^-}$ (in GeV). Comparing this result with (2), we see that $d\sigma(\nu_\mu e \to \nu' e)/dE_e'$ for small m_{M^-} is dominated by the weak-neutral-current (w.n.c.) contribution to $d\sigma(\nu_\mu e \to \nu_\mu e)/dE_e'$. However, we notice that the situation is reversed in the range of $m_{M^-} \gtrsim 20$ GeV where $d\sigma(\nu_\mu e \to \nu' e)/dE_e'$ is larger than $d\sigma(\nu_\mu e \to \nu_\mu e)_{\rm w.n.c.}/dE_e'$; for example, the data of Ref. 5 as regards the total number of $\nu_\mu e$ events are consistent with $\sin\varphi/\cos^2\varphi = 3$ and $m_{M^-} = 20$ GeV or with $\sin\varphi/\cos^2\varphi = 2$ and $m_{M^-} = 30$ GeV. However, because of the spectrum of recoil electrons according to Eq. (2), we expect most of the events to have low energy for the recoil electron[15]; this is a characteristic of any transition magnetic moment scheme. We also note that the type of model (3) can be found in extended gauge groups provided that the same gauge boson couples to both the $V+A$ and the $V-A$ parts of the M^- currents. In addition, *it is clear the phenomenology of $\nu_\mu \leftrightarrow \nu'$ transition magnetic moment described by Eqs. (1) and (2) is independent of any gauge model.*

One might have expected that a similarly large charge radius[16] (diagonal or transition) exists for the type of model (3). However, the charge radius is not enhanced by the mechanism of (3). Dimentional estimation shows that the diagonal squared charge radius, a^2, goes as M_W^{-2}, and explicitly,[17]

$$a^2 \sim (G_F/2\sqrt{2}\pi^2)[c_1 + c_2\ln(M_W^2/m_\mu^2)],$$

i.e. $a \sim 5\times 10^{-17}$ cm in the usual WS model. The type of model in (3) changes this result by introduction of an additional term $c_1' + c_2'\ln(M_W^2/m_{M^-}^2)$ which will remain small in gauge theories. Therefore, though a^2 arises in higher orders in gauge theories it is not important compared to the weak neutral-current interaction.[9]

If ν' is produced,[18] it mainly decays to $\nu_\mu + \gamma$

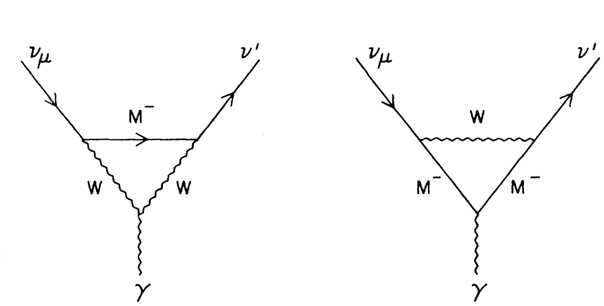

FIG. 1. Diagrams for a ν_μ-ν' transition magnetic moment.

with a decay width estimated[19] from the contribution of Fig. 1,

$$\Gamma(\nu' \to \nu_\mu \gamma) = \tfrac{1}{4}\alpha f'^2 (m'/m_e)^2 m'. \qquad (5)$$

For $f' \approx 10^{-8}$ and $m' \approx 100$ MeV, the lifetime of ν' is 0.95×10^{-9} sec. The branching ratio for $\nu' \to \nu_\mu e\bar{e}$ is $2\alpha/3\pi[\ln(m'/2m_e) - \frac{7}{12}]$ which is negligible.

In this Letter, we have explored the possibility of the neutrinos ν_μ (ν_e) possessing large transition magnetic moments relative to a massive neutrino ν'. Such transition magnetic moments will have interesting effects on several processes but may have escaped detection so far. In general, for ν_μ incident on a hadron target, we would have enough energy to produce ν' but the relevant effects would still be small because of the large Q^2 in this case. For ν_μ incident on an electron target, $\nu_\mu + e \to \nu' + e$ events may be more frequent than the $\nu_\mu + e \to \nu_\mu + e$ events at high energies, but may not be produced at low energies because of the ν' threshold effect.

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[1]J. Bernstein, M. Ruderman, and G. Feinberg, Phys. Rev. 132, 1227 (1963).

[2]J. Bernstein and T. D. Lee, Phys. Rev. Lett. 11, 512 (1963).

[3]J. E. Kim, V. S. Mathur, and S. Okubo, Phys. Rev. D 9, 3050 (1974); D. Yu. Bardin and O. A. Mogilevsky, Lett. Nuovo Cimento 9, 549 (1974); J. D. Bjorken, SLAC Report No. SLAC-PUB-2062, 1977 (unpublished); M. A. B. Bég, W. J. Marciano, and M. Ruderman, Phys. Rev. D 17, 1395 (1978).

[4]This kind of particle seems to be allowable even in the cosmological analysis. See, for example, D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Astrophys. J. 221, 327 (1978), and Phys. Rev. D 17, 1529 (1978).

[5]Our interest in this problem was kindled by a report by C. Pascaud, given in Proceedings of the International Conference on Neutrino Physics and Neutrino Astrophysics, West Lafayette, Indiana, 28 April–2 May, 1978 (to be published). However, our considerations here do not depend on any assumptions about the experiment on $\nu_\mu e \to \nu_\mu e$. At present there are conflicting results on this: P. Alibran *et al*. [CERN Report No. CERN/EP/PHYS 87-6, 1978 (unpublished)] give $\sigma_{tot}(\nu_\mu e \to \nu_\mu e) = [(7.3^{+3.3}_{-2.6}\text{–}8.2^{+3.7}_{-2.8}) \times 10^{-42}\ \mathrm{cm^2/GeV}]E_\nu$ while C. M. Cnops *et al*. {preceding Letter [Phys. Rev. Lett. 41, 357 (1978)]} give $\sigma_{tot}(\nu_\mu e \to \nu_\mu e) = [(1.8 \pm 0.8) \times 10^{-42}\ \mathrm{cm^2/GeV}]E_\nu$. [See also H. Faissner *et al*., Phys. Rev. Lett. 41, 213 (1978).]

[6]J. E. Kim, Phys. Rev. D 14, 3000 (1976).

[7]For a distinct-neutrino case ($\nu' \neq \nu_\mu$), the term $\bar{\nu}_\mu \sigma^{\mu\alpha} q_\alpha \gamma_5 \nu'$ is as important as the other term.

[8]F. J. Hasert *et al*., Phys. Lett. 46B, 138 (1973); A. Benvenuti *et al*., Phys. Rev. Lett. 32, 800 (1974).

[9]Kim, Mathur, and Okubo, Ref. 3.

[10]F. J. Hasert *et al*., Phys. Lett. 46B, 121 (1973); F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. 37, 315 (1976).

[11]The difference between Eq. (2) and the result in Ref. 9 arises from the inclusion of a factor 2 due to the additional $\sigma^{\mu\alpha} q_\alpha \gamma_5$ term and from the threshold effect.

[12]For a comparison with the result of Alibran *et al*. (Ref. 5), we subtracted $\sigma_{\nu_\mu e}{}^{WS} \approx 0.5 \times 10^{-40}$ cm^2 from the total cross section $(3.6^{+1.7}_{-1.3}) \times 10^{-40}\ \mathrm{cm^2} < \sigma_{\nu_\mu e} < (4.1^{+1.9}_{-1.4}) \times 10^{-40}$ cm^2. Also we have folded in the energy spectrum of the CERN-Gargamelle ν_μ beam, and taken into account only the low-energy group of recoil electrons.

[13]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967), and 27, 1688 (1972); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p. 367.

[14]For a large value of $|\sin\varphi|$, the overall strength of the neutral-current parameter is increased compared to the charged ones. Therefore, we need Higgs triplets, singlets, etc., in addition to the doublets so that the value $\kappa \equiv M_Z{}^2/M_W{}^2 \sec^2\theta_W$ can be bigger than 1 without upset of the phenomenology of the WS model. Also, if $N°$ in (3) is identified as ν', we have the following delicate problem. In principle, the ν' mass can be determined from $K_{\mu 3}$ decay: $K_{\mu 3} \to \pi\mu\nu_\mu$ and $K_{\mu 3} \to \pi\mu\nu'$. The identification of the $\pi\mu\nu'$ contribution is, however, difficult because of the *a priori* unknown $K \leftrightarrow \pi$ form factor. On the other hand, the determination of the limit on m_{ν_μ} by examination of the high-energy end of the μ spectrum is unaffected by the presence of ν' since $m' \gg m_{\nu_\mu}$. Note in this connection that $\Gamma(K \to \pi\mu\nu')/\Gamma(K \to \pi\mu\nu_\mu) \cong \tan^2\varphi \times$ (phase-space factor). For data, see A. C. Callahan *et al*., Phys. Rev. 150, 1153 (1966). Hence the $K_{\mu 2}$ decay may be used for determination of m': $K_{\mu 2} \to \mu\nu_\mu$ ($|\vec{p}_\mu| \cong 236$ MeV) and $K_{\mu 2} \to \mu\nu'$ ($|\vec{p}_\mu| \cong 225$ MeV for $m' \approx 100$ MeV). However, the accuracy of the present data [D. R. Botterill *et al*., Phys. Rev. 171, 1402 (1968)] is not sufficient to separate out the $K_{\mu 2} \to \mu\nu'$ mode. In addition, for $m_e \ll m'' < 500$ MeV, where ν'' is the counterpart of ν' in the electron family and m'' is its mass, the ratio $[\Gamma(K^+ \to e^+\nu_e) + \Gamma(K^+ \to e^+\nu'')]/[\Gamma(K^+ \to \mu^+\nu_\mu)$

$+\Gamma(K^+\to\mu^+\nu')$] will be much larger than the experimental value 1.9×10^{-5} [R. Macek *et al.*, Phys. Rev. Lett. 22, 32 (1969)], since the helicity argument no longer applies. Hence, we should set $m''>500$ MeV. With these values of m'' and m' the limit $m_{\nu_\tau}\lesssim 250$ MeV, obtained by examination of the high-energy end of the e or μ spectrum from τ decay, is not affected since $m'', m' \gg m_{\nu_e}, m_{\nu_\mu}$.

[15]If the reported data are not due to statistical fluctuation, they can be separated into two groups, one the low-energy group and the other the high-energy group. Certainly, the interaction (1) describes the low-energy group pretty well. But whether this grouping is a statistical fluctuation or a real effect is unknown at present. These points were stressed by H. Primakoff (private communication).

[16]In gauge theories, the charge radius is not a gauge-invariant quantity. Our estimate of this quantity is performed in a special gauge, e.g., in the 't Hooft-Feynman gauge.

[17]See, for example, J. E. Kim, thesis, University of Rochester, 1975 (unpublished).

[18]D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, in Proceedings of the International Conference on Neutrino Physics and Neutrino Astrophysics, West Lafayette, Indiana, 28 April–2 May 1978 (to be published), consider possible searches for ν' in a heavy-liquid bubble chamber.

[19]See, for example, J. E. Kim, Phys. Rev. D 16, 172 (1977).

Search for Long-Lived Heavy Particles

D. Cutts, R. S. Dulude, B. W. Hughlock, R. E. Lanou, and J. T. Massimo
Brown University, Providence, Rhode Island 02912

and

A. E. Brenner, D. C. Carey, J. E. Elias, P. H. Garbincius, and V. A. Polychronakos
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

J. Butler
University of Illinois, Urbana, Illinois 61801

and

M. T. Chiaradia, C. De Marzo, C. Favuzzi, G. Germinario, L. Guerriero, P. Lavopa, G. Maggi, F. Posa, G. Selvaggi, P. Spinelli, and F. Waldner
Istituto di Fisica and Istituto Nazionale di Fisica Nucleare, Bari, Italy

and

D. S. Barton, G. W. Brandenburg, W. Busza, T. Dobrowolski, T. Duddy, J. I. Friedman, C. Halliwell, H. W. Kendall, T. Lyons, B. Nelson, L. Rosenson, M. Tartaglia, R. Verdier, and C. C. Young
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

J. Nassalski and T. Siemiarczuk
Institute of Nuclear Research, Warsaw, Poland
(Received 30 May 1978)

We have performed a high-sensitivity search for massive long-lived particles produced at 2.5 mrad by 400-GeV/c protons on a beryllium target using time-of-flight, Cherenkov, and calorimetric techniques. A total of 10^{11} light particles ($\pi^-, K^-, \bar{p}$) was sampled at 70 GeV/c. This experiment places a limit of 1.1×10^{-37} cm^2/(GeV/c)$^2\cdot$nucleon on the invariant cross section for the production of stable particles in the mass range of 4 to 10 GeV/c^2.

A search for new, massive, long-lived particles produced in collisions between 400-GeV/c protons and beryllium nuclei has been performed at Fermilab. The apparatus was sensitive to particles with masses between 2 and 10 GeV/c^2 and with charge $\geq \frac{2}{3}e$. This experiment was approx-