LIMITS ON HIGH-ENERGY WEAK-INTERACTION CROSS SECTIONS AND THE W-PAIR STRONG-INTERACTION MODEL

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Deep-mine neutrino experiments set an upper limit of 10^{-33} cm^2 for the reaction cross section of ν_μ-nucleon interaction at 10^3 GeV; the implications of this on the W-pair strong-interaction model are discussed.

Recently there has been a renewed interest in the possibility that at high energies certain weak semileptonic[1] or purely leptonic[2] interactions may become much stronger than usually assumed. We consider first phenomenologically crude limits which one can set on some of the semileptonic cross sections at high energies at the present time, and then comment on their implications on a particular model.

(a) The total cross-section of the μ-nucleon interaction $\sigma(\mu N)$.—The simplest limit one can set on this is just from the known penetrability of muons deep underground. Atmospheric muons have been detected at a depth[3,4] of around 8000 m (w.e.) with no anomalous reduction from the expected intensity.[5] These muons will have energies $\gtrsim 10^{12}$-10^{13} eV over a large portion of their path; therefore, there is approximately a limit of $\sigma(\mu N) < 10^{-30}$ cm^2 at a c.m. energy of $E_{\text{c.m.}}^2 \simeq 10^3$-$10^4$ GeV^2. We will not worry about the finer points of such an estimate because the limit on the weak-interaction cross sections between muons and nucleons can in fact be greatly improved if one assumes that it is comparable with that on $\sigma(\nu_\mu N)$ as discussed below.

(b) The cross sections of the ν_μ-nucleon interaction $\sigma(\nu_\mu N)$.—Neutrino-induced events, some inelastic, have been detected at 8800 m (w.e.)[4] and 7500 m (w.e.)[6] at one to two times the expected frequency. The statistics are still poor (30 events and 10 events, respectively); so thus far the total rates can be considered as compatible with no radical departure from the usual weak-interaction strength. If, on the other hand, the ν_μ-nucleon reaction cross section for producing a muon should rise continuously in some fashion from the 10^{-38}-10^{-37} cm^2 at 10 GeV to 10^{-33} cm^2 at a neutrino laboratory-system energy of 10^3 GeV and beyond, then from the cosmic-ray neutrino spectrum[7] one may estimate conservatively that the above rates will begin to be exceeded. Thus the reaction cross section $\sigma(\nu_\mu N) < 10^{-33}$ cm^2 at $E_{\text{c.m.}}^2 \simeq 10^3$ GeV^2.

Although the above limits on semileptonic cross sections are obviously crude, the experiments above already have implications for the W-pair strong-interaction theory.[1] One of the reasons for the renewed interest in this model is the possible connection with the lack of $\sec\theta$ effects for cosmic-ray muons above 1000 GeV reported by Bergeson et al.[8] If beyond a certain energy the weak production of leptons becomes significant in hadron collisions, it will reduce the $\sec\theta$ dependence of sea-level muon flux in two ways: First, the muons produced directly in the first collisions of the primary will not have the $\sec\theta$ dependence; secondly, when an energetic pion collides with an air molecule, there will also be a finite probability of producing energetic muons. If this latter probability amounts to 10%, the $\sec\theta$ effect will be reduced by half since only one out of ten pions of 10^3 GeV will materialize into a muon of comparable energy through decay.

Thus the W-pair strong-interaction theory has been considered as one of the possible ways of "instant" muon production in hadron collisions.[9] However, it seems to us that this is possible only if the mass of the W is close to the lower limit[10] of 2.5 GeV. Even then, the production cross section for W pairs, estimated from a statistical model[11] with a temperature $\simeq 140$-160 MeV, is only about 10^{-35} cm^2. More important is the consideration that each increase in M_W by 1 GeV will decrease the cross section by more than five orders of magnitude. So if W-pair production is responsible for the lack of $\sec\theta$ dependence at all, M_W must not be much heavier than 2.5 GeV.

On the other hand, if M_W is close to 2.5 GeV, then the cross section of the reaction $\nu_\mu N \to \mu N W$ is fairly large. An order of magnitude estimate, in which at least the baryon form factor is approximately taken into account, can be obtained by multiplying the computed electromagnetic production cross section[12] by $Af^2/Z^2\alpha^2$, where f is an effective dimensionless coupling constant characterizing the strength of the W-pair interaction with baryons. We find that in order not to exceed the counting rates of the experiments in (b), $f^2<10^{-3}$. This estimate of f^2 may be somewhat low since the diagram for W production through a W-pair strong interaction corresponds to only one of the two contributing diagrams for electromagnetic production; nevertheless, it should not be three or four orders of magnitude off, which would be necessary for the W-pair strong interaction to be as strong as the usual strong interactions.

One sees that either M_W must be considerably larger than 2.5 GeV, or the W-pair interaction is not too strong, in order to agree with the deep-mine neutrino experiments. In either case it will be difficult to explain the lack of $\sec\theta$ dependence of sea-level muons above 10^3 GeV if it is further substantiated by future experiments, on the basis of a W-pair strong-interaction model.[13]

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[1]For example, lepton productions in lepton-hadron and hadron-hadron collisions could be more copious in the W-pair strong-interaction theory. T. Ericson and S. L. Glashow, Phys. Rev. 133, B130 (1964); S. V. Pepper, C. Ryan, S. Okubo, and R. E. Marshak, Phys. Rev. 137, B1259 (1965); G. Feinberg, Phys. Rev. 134, B1295 (1964); S. Pakvasa, S. F. Tuan, and T. T. Wu, Phys. Rev. Letters 20, 1546 (1968), and to be published; C. G. Callan, Jr., Phys. Rev. Letters 20, 809 (1968).

[2]For example, in the models of M. Gell-Mann, M. L. Goldberger, N. Kroll, and F. Low, to be published, it is possible for some diagonal interactions (but not all diagonal ones) to be of a very different strength from the usual weak interactions, even at moderate energies. The couplings $(e\nu)(e\nu)$ and $(\mu\nu_\mu)(\mu\nu_\mu)$ are diagonal. However, at low energies the experiment of Cowan and Reines [Phys. Rev. 107, 528 (1957)] sets an upper limit on the $(e\nu)$ scattering cross section of $\sigma<4\times10^{-43}$ cm^2, whereas C.-W. Chin et al. [Ann. Phys. (New York) 39, 280 (1966)] concluded from the lifetime of ultraviolet dwarfs that the lower limit to the $(e\nu)(e\nu)$ coupling is close to half of the universal-Fermi-interaction strength. The latter conclusion is of course subject to the uncertainties of our knowledge of stellar structure, but the upper and lower limits together imply that no radically different strength is expected for the $(e\nu)(e\nu)$ coupling at low energies.

[3]M. Menon et al., Phys. Letters 5, 272 (1963).

[4]F. Reines, Proc. Roy. Soc. (London), Ser. A 301, 125 (1967).

[5]By this we mean the approximate agreement of muon spectrum from depth-intensity curves and from burst measurements, and, for muon energies below 500 GeV, also from magnetic spectrometer measurements. The spectrum deduced from γ measurements need not agree if the high-energy muons are not from pion and kaon decays. The spectrum has been summarized in J. L. Osborne et al., Proc. Phys. Soc. (London) 84, 911 (1964).

[6]M. Menon et al., Proc. Roy. Soc. (London), Ser. A 301, 137 (1967).

[7]See, for example, J. L. Osborne et al., Proc. Phys. Soc. (London) 86, 93 (1965). The possibility of direct production of leptons is expected to increase, rather than to reduce, the given high-energy ν flux, and so will not change the conclusion below.

[8]H. E. Bergeson et al., Phys. Rev. Letters 19, 1487 (1968).

[9]C. G. Callan, Jr., and S. L. Glashow, Phys. Rev. Letters 20, 779 (1968); Pakvasa, Tuan, and Wu, Ref. 1.

[10]G. Bernardini et al., Phys. Letters 13, 86 (1964); R. Burns et al., Phys. Rev. Letters 15, 42 (1965).

[11]I. N. Sisakian, E. L. Feinberg, and D. S. Chernavski, Zh. Eksperim. i Teor. Fiz. 52, 545 (1967) [translation: Soviet Phys.—JETP 25, 356 (1967)]; R. Hagedorn, Nuovo Cimento Suppl. 3, 147 (1965). The use of statistical models in heavy-pair productions is in our opinion more reliable than in processes where peripheral productions may be expected to dominate, such as in the production of a single isobar.

[12]See, for instance, G. von Gehlen, Nuovo Cimento 30, 859 (1963), who gives asymptotic curves and formulas for the electromagnetic W production cross section.

[13]In this respect the second alternative is preferable because if the interaction is weaker, then equilibrium may not be reached and the production cross section could exceed the statistical estimate. See also the remarks on "leakage" by Sisakian, Feinberg, and Chernavskii in Ref. 11.