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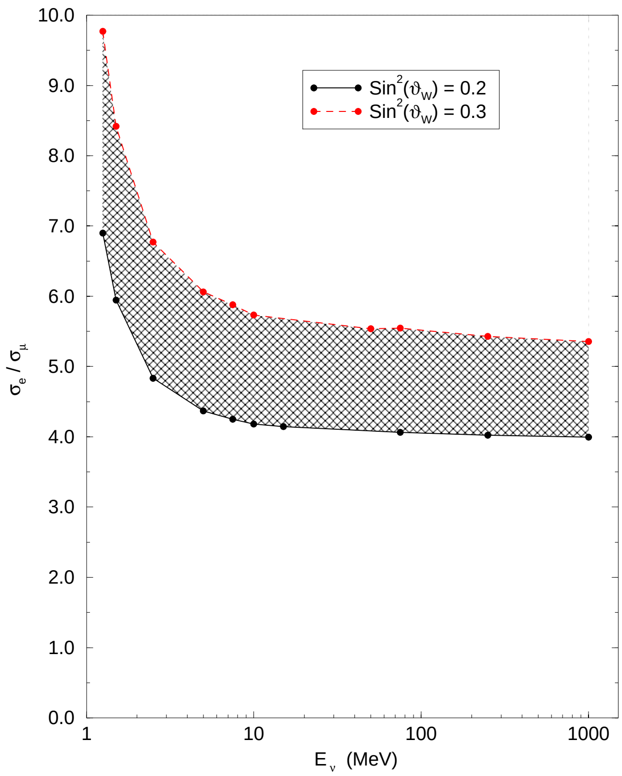

Figure 2. The ratio of electron neutrino cross section to the muon neutrino cross sectin as a function of neutrino energy for a range of values of the Weinberg angle.

ate flavor production beyond the first generation and to nondegenerate flavor production using appropriate choices for the constants in Eq. (1).

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We have also tested the analytic approximation M_0 for M_{ch} against exact numerical calculations for the full neutrino cross sections, and we find excellent agreement. This agreement indicates the term M' does not contribute appreciably, and thus the simplified form, M_0, may be used for various applications.

From the laboratory detection angle, the event signature would be the produced pair. Such pairs should be distinct from those arising from de-excitation of nuclei, as the energy available to the latter pair is fixed by the de-excitation energy of the nucleus and the correlation signature of such a de-excitation pair. In contrast, the energy distributions of the neutrino-initiated direct pairs display continuum characteristics, and the angular distributions respect helicity constraints of the electroweak vertex and the physics of the photon vertex.

The compact form of the matrix element squared in its M_0 form and the similarity of the weak leptonic sector with the similar quantity from e-ν scattering suggested the possibility of processes like this serving as a tool in low-energy explorations of $\sin^2\theta_w$. In fact, we could express the ratio of $ig\nu_e$ to ν_μ cross sections as

$$\frac{\sigma_{\nu e}}{\sigma_{\nu\mu}} = \frac{\{(s+1)^2B_1 + s^2B_2 + m^2s(s-1)B_3\}}{\{(s-1)^2B_1 + s^2B_2 + m^2s(s-1)B_3\}}. \tag{6}$$

B_1, B_2, and B_3 can be found numerically at given energies, and $\mathrm{s} = \sin^2\theta_W$.

We present in Fig. 2 the above ratio as a function of energy for a range of s. Other similar ratios that may be of interest to experimentalists can be easily computed. For instance, the ORLaND proposal[11] proposes to use a combined electron-neutrino, anti-muon neutrino cross section in the ratio to determine s from electron scattering. This choice is influenced by the time distributions of the SNS neutrinos. Similar incident particle combinations could be used in the ratios for the pair production cross sections.

The connection between the processes studied in this paper and photon-neutrino pair production can be easily seen by cutting off the nuclear legs in the Feynman diagrams of Fig. 1. We would like to thank Professor Leo Stodosky for pointing out the possibility of using the neutrino-nucleus pair production as an experimental tool to study the photon-neutrino cross sections.[12]

The question of possible roles in astrophysics also arises. What might be the astrophysical environments to spawn such neutrino-bremstrahlung pairs? High Z environments such as pre-collapse supernova cores, scenes of the stalled shock, or the neutrino-driven winds hosting the r-process and neutrino nucleosynthesis suggest themselves as potential sites. The density of the Fermi sea, however, would inhibit low-energy electron production in pre-collapse cores.

Including flavor variety, the formalism can be readily extended to degenerto the nucleus. P and q are connected to the four-momenta of the initial and final nuclei through q = p-p$'$ and P = p+p$'$. F(q^2) represents the nuclear form factor, and the four-momenta of the external legs are denoted in Fig. 1. The Fierz rotation has been applied to the charged current channel as is customary.

Introducing the phase space factors, the cross section can be written in terms of the matrix element as

$$\sigma = \frac{1}{4E_o E_p} \int \frac{d^3k'}{2E'} \frac{d^3r_+}{2E_+} \frac{d^3r_-}{2E_-} \frac{d^3p'}{2E_{p'}} \sum_{spins} \mid M \mid^2 \frac{(2\pi)^4}{(2\pi)^{12}} \delta^4(k'+r_+ + r_- - k - q). \tag{2}$$

The square of the matrix element is summed over final spins. There is no averaging over initial spins, as the neutrino is helical. The delta function ensures four-momentum conservation for the process. Conventions for phase space factors, gamma matrices, and spinor normalization are those of Bjorken.[7] The phase space is evaluated numerically using Monte Carlo techniques.

The charged lepton sector of the matrix element of Eq. (1) can be reduced to a compact form by using the dirac equation and expressed as the sum of two terms. $M_{ch} = M_0 + M'$, where

$$M_0 = [\bar{U}(r_-)\gamma_\mu(a - b\gamma_5)V(r_+)]\Big[\frac{2(Pr_-)}{(Q_-^2 - m^2)} - \frac{2(Pr_+)}{(Q_+^2 - m^2)}\Big] \tag{3}$$

and

$$M' = \bar{U}(r_-)\Big[- \frac{PQ\gamma_\mu(a - b\gamma_5)}{(Q_-^2 - m^2)} + \gamma_\mu \frac{(a - b\gamma_5)QP}{(Q/r^2 - m^2)}\Big] \tag{4}$$

such that

$$M = \frac{G}{\sqrt{2}} \frac{(Ze^2}{q^2} [\bar{U}(k')\gamma^\mu(1 - \gamma_5)U(k)] M_{ch}. \tag{5}$$

This decomposition allows us to isolate the part (M_0) that coincides with the standard electroweak leptonic processes like e-ν scattering and muon decay, for which the spin summations and angular correlations are well known. We have shown numerically that the M$'$ term contribution is small over a wide range of neutrino energies. This is not surprising since for real photon channels this term does not contribute, and the two cross sections should approach each other as $q^2 > 0$, in accordance with the equivalent photon descriptions.[8,9]

We have compared our results calculated for ^{56}Ni in the V-A approximation with similar results from Czyz.[10], and observe excellent agreement.

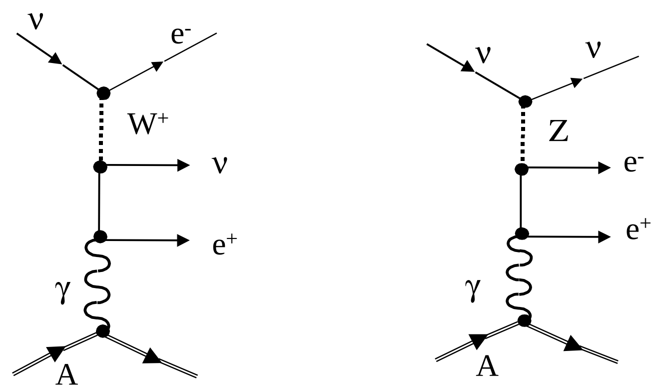

Figure 1. Feynman diagrams for both charged current and neutral current pair production in the field of a nucleus.

by both charged and neutral current channels, while the muon neutrino can only do this via neutral currents. The processes can also be described as bremstrahlung of charged pairs by neutrinos in the field of nuclei and represented by the Feynman diagrams of Fig. 1. We restrict our study to spin-zero nuclei that respond coherently and elastically. At the energies of interest, the effective Lagrangian approximation of the Standard Model, where the gauge boson propagators are collapsed to local couplings, may be used. Since the electroweak sectors in Fig. 1 represent purely leptonic currents, the form of the effective Lagrangian is well known.[4,6]

The second-order S-matrix elements corresponding to electron–positron pair production by neutrinos can be written in a generalized form in terms of the appropriate effective Lagrangian as

$$M = \frac{G}{\sqrt{2}}(Ze^2)F(q^2)\frac{P_\alpha}{q^2}[\bar{U}(k')\gamma^\mu(1-\gamma_s)U(k)]$$
$$[\bar{U}(r_-)\gamma_\alpha\frac{1}{(Q_- - m)}\gamma_\mu(a-b\gamma_s)\gamma_\mu(a-b\gamma_s)\frac{1}{(Q_+ - m)}\gamma_\alpha V(r_+)] \quad (1)$$

where Q_- = r_--q and Q)+ = q-r_+, a = -1/2 + 2 $\sin^2\theta_w$ and b = -1/2 for ν_μ, a = +1/2 + 2 $\sin^2\theta_2$ and b = +1/2 for ν_3 and a = 1, b = 1 for the V-A case.[6,4]

Equation (1) includes the direct and cross terms. U and V refer to the spinors for the respective particles or antiparticles. Q_- and Q_+ are the four-momenta of the electron and positron propagators, respectively. 'e' is the usual electromagnetic coupling constant, and q is the four-momentum transfer

FLAVOR-DEGENERATE PAIR PRODUCTION IN NEUTRINO–NUCLEUS COLLISIONS

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Standard Model cross sections for flavor-degenerate pair production in neutrino–nucleus collisions are presented for the first time. In the V-A approximation, results are seen to agree with published work from the pre-neutral current era. Cross sections are of the order of 10^{-41} cm^2 for ν_c-gold collisions for 100 MeV incident neutrinos. Signatures of such events and similarities with leptonic electroweak channels are discussed.

Pair production in neutrino-nucleus collisions is representative of a class of processes which produce lepton-antilepton pairs in the electroweak sector and couple these electromagnetically to nuclei. As the nucleus participates via virtual photon exchange, the resultant cross sections are of order $(\mathrm{GZ}\alpha)^2$, where G is the Fermi constant and $(\mathrm{Z}\alpha)$ represents the electromagnetic coupling to the nucleus. These may be compared to processes of order $(\mathrm{G}2\alpha)^2$, including bremstrahlung of neutrino pairs by electrons,[1] neutrino–photon collisions,[2] and alpha order corrections to the lowest order electroweak channels.[3] The contributions from pair production could therefore surpass the $(\mathrm{G}^2\alpha)$ ones for values of Z exceeding 12, depending on the other effects such as phase space. Neutrino–electron scattering channels[4] are also of comparable order at sufficiently high Z values. The leading order neutrino–nucleus cross sections, behaving as $(\mathrm{G}^2\mathrm{A})$,[5] remain higher than the pair-production channel.

In this conference report, we focus on the production of first-generation flavor pairs only and consider incident neutrinos of electron and muon flavor. The channels can be represented as $\nu_i + \mathrm{A} \rightarrow \nu_i + \mathrm{A} + \mathrm{e}^+ + \mathrm{e}^-$, where i includes all flavors. The electron neutrinos can initiate the reaction