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Pion Mechanism for the Process $\gamma+\gamma\to\nu+\bar{\nu}$

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A mechanism involving pions in the intermediate state is considered for the process $\gamma+\gamma\to\nu+\bar{\nu}$. Fixed-momentum dispersion relation methods are employed to evaluate the cross sections and luminosities for both electron-type and muon-type neutrinos. Comparison is made between this mechanism and previous results involving intermediate bosons.

I. GENERAL DISCUSSION

The process $\gamma+\gamma\to\nu+\bar{\nu}$ vanishes to lowest order in the Fermi theory of weak interactions.[1] It has been analyzed, assuming an intermediate-boson theory of weak interactions.[2] In this paper, we consider a mechanism for this process in the Fermi theory. The mechanism involves charged pions in the intermediate state, specifically, direct coupling of a pion to a charged lepton and a neutrino. The coupling constant G' is known phenomenologically from the decay of the pion[3]:

$$G'=fG\ , \tag{1.1}$$

$$f=0.95m_\pi\ , \tag{1.2}$$

$$G=10^{-5}/M_p^{\,2}\ . \tag{1.3}$$

We employ a fixed-momentum dispersion relation approach in the manner of Ref. 2. The lowest-order contribution to the matrix element is of order ω^3, where ω is the center-of-mass energy of each photon. For both the production of electron-type and muon-type neutrinos, the crossed-channel contributions are found to be very small compared to the direct-channel contributions.

The interaction Lagrangian is

$$L_{\text{int}}=L_{e\gamma}+L_{\pi\gamma}+L_{\pi l\nu\gamma}\ . \tag{1.4}$$

The expression for $L_{\pi l\nu\gamma}$ is

$$L_{\pi l\nu\gamma}=\frac{G}{\sqrt{2}}\,(J_\alpha l_\alpha+J_\alpha^\dagger l_\alpha^\dagger)\ , \tag{1.5}$$

where

$$J_\alpha=f\left(\frac{\partial}{\partial x_\alpha}-ieA_\alpha\right)\phi_\pi\ , \tag{1.6}$$

$$l_\alpha=\bar{e}\gamma_\alpha(1+\gamma_5)\nu_e+\bar{\mu}\gamma_\alpha(1+\gamma_5)\nu_\mu\ . \tag{1.7}$$

II. ABSORPTIVE PARTS

The absorptive part $A(T)$ is obtained from the S-matrix unitarity formula

$$\begin{aligned}A(T)&=-\tfrac{1}{2}i\langle f|T-T^\dagger|i\rangle\\&=-\tfrac{1}{2}(2\pi)^4\sum_n\langle f|\,T\,|n\rangle\langle n|\,T^\dagger|i\rangle\,\delta(P_n-P_i)\ ,\end{aligned} \tag{2.1}$$

where

$$S_{fi}=\delta_{fi}+R_{fi}\ , \tag{2.2}$$

$$R_{fi}=-(2\pi)^4 i\delta(P_f-P_i)T_{fi}\ . \tag{2.3}$$

We approximate Eq. (2.1) by including only two-particle intermediate states. Specifically, we include $|e^+(\mu^+), e^-(\mu^-)\rangle$, $|\pi^+,\pi^-\rangle$ states in the direct channel and $|\pi, e(\mu)\rangle$ states in the crossed channel. The electrons and muons in the intermediate states are for $\langle\nu_e,\bar\nu_e|$ and $\langle\nu_\mu,\bar\nu_\mu|$ final states, respectively.

Hence, for the direct channel,

$$\begin{aligned}A(T)\cong{}&-\tfrac{1}{2}(2\pi)^4\Big[\sum\langle\nu,\bar\nu|T|l^+,l^-\rangle\langle l^+,l^-|T^\dagger|\gamma_1,\gamma_2\rangle\delta(p_{l^+}+p_{l^-}-k_1-k_2)\\&+\sum\langle\nu,\bar\nu|T|\pi^+,\pi^-\rangle\langle\pi^+,\pi^-|T^\dagger|\gamma_1,\gamma_2\rangle\delta(p_{\pi^+}+p_{\pi^-}-k_1-k_2)\Big]\\={}&-\tfrac{1}{2}(2\pi)^4\Big[\sum M_{2a}M_{1a}^\dagger\delta(p_{l^+}+p_{l^-}-k_1-k_2)+\sum M_{2b}M_{1b}^\dagger\delta(p_{\pi^+}+p_{\pi^-}-k_1-k_2)\Big]\ ,\end{aligned} \tag{2.4}$$

where

$$M_{1a}=\langle\gamma_1,\gamma_2|-iT|e^+(\mu^+),e^-(\mu^-)\rangle\ , \tag{2.5}$$

$$M_{1b}=\langle\gamma_1,\gamma_2|-iT|\pi^+,\pi^-\rangle\ , \tag{2.6}$$

$$M_{2a}=\langle\nu,\bar\nu|-iT|\,e^+(\mu^+),e^-(\mu^-)\rangle\ , \tag{2.7}$$

$$M_{2b}=\langle\nu,\bar\nu|-iT|\pi^+,\pi^-\rangle\ . \tag{2.8}$$

The respective graphs are shown in Figs. 1–4.

$$M_{1a}=\frac{ie^2}{(2\omega_1)^{1/2}(2\omega_2)^{1/2}}\,\bar v(p-k_1-k_2)\left(\not\epsilon_2\frac{i(\not p-\not k_1)-m}{(p-k_1)^2+m^2}\not\epsilon_1+\not\epsilon_1\frac{i(\not p-\not k_2)-m}{(p-k_2)^2+m^2}\not\epsilon_2\right)u(p)\,, \tag{2.9}$$

$$\begin{aligned}M_{1b}=\frac{ie^2}{(2\omega_{\pi^+})^{1/2}(2\omega_{\pi^-})^{1/2}(2\omega_1)^{1/2}(2\omega_2)^{1/2}}&\left(\frac{(2p_\pi-k_1)\cdot\epsilon_1(2p_\pi-2k_1-k_2)\cdot\epsilon_2}{(p_\pi-k_1)^2+m_\pi^{\,2}}\right.\\&\left.+\frac{(2p_\pi-k_2)\cdot\epsilon_2(2p_\pi-2k_2-k_1)\cdot\epsilon_1}{(p_\pi-k_2)^2+m_\pi^{\,2}}-2\epsilon_1\cdot\epsilon_2\right)\ ,\end{aligned} \tag{2.10}$$

$$M_{2a}=\frac{iG'^2}{2}\,\bar v(p-p_\nu-p_{\bar\nu})(\not p_\nu-\not p)(1+\gamma_5)v(-p_{\bar\nu})\frac{1}{(p_\nu-p)^2+m_\pi^{\,2}}\,\bar u(p_\nu)(1-\gamma_5)(\not p_\nu-\not p)u(p)\ , \tag{2.11}$$

$$M_{2b}=\frac{iG'^2}{2(2\omega_{\pi^+})^{1/2}(2\omega_{\pi^-})^{1/2}}\,\bar u(p_\nu)(1-\gamma_5)\not p_\pi\frac{i(\not p_\nu-\not p_\pi)-m}{(p_\nu-p_\pi)^2+m^2}(\not p_\nu+\not p_{\bar\nu}-\not p_\pi)(1+\gamma_5)v(-p_{\bar\nu})\ . \tag{2.12}$$

The lepton mass m in the above equations is the electron mass for $\langle\nu_e,\bar\nu_e|$ final states and the muon mass for $\langle\nu_\mu,\bar\nu_\mu|$ final states.

For the crossed channel,

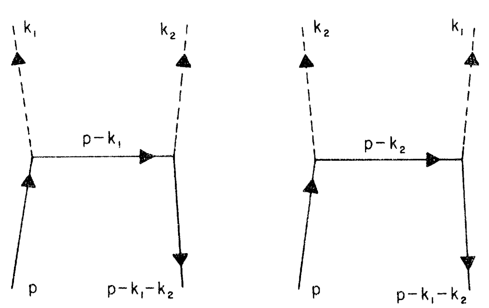

FIG. 1. Graphs for M_{1a}.

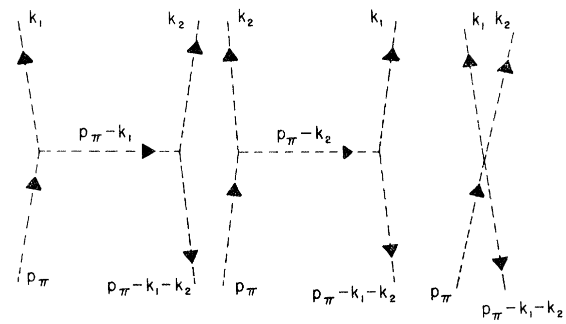

FIG. 2. Graphs for M_{1b}.

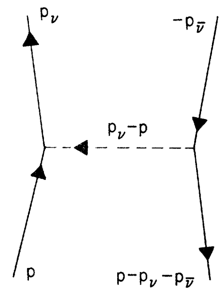

FIG. 3. Graph for M_{2a}.

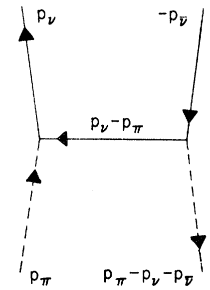

FIG. 4. Graph for M_{2b}.

$$A^c(T)\cong -\tfrac{1}{2}(2\pi)^4\sum\langle\gamma_2,\nu|T|l,\pi\rangle\langle l,\pi|T^\dagger|\gamma_1,\nu'\rangle\delta(p_l+p_\pi-k_1-p_{\nu'})=-\tfrac{1}{2}(2\pi)^4\sum M_2^c M_1^{c\dagger}\delta(p_l+p_\pi-k_1-p_{\nu'}) \;, \tag{2.13}$$

where

$$M_1^c=\langle\gamma_1,\nu'|-iT|e(\mu),\pi\rangle \;, \tag{2.14}$$

$$M_2^c=\langle\gamma_2,\nu|-iT|e(\mu),\pi\rangle \;. \tag{2.15}$$

The graphs for M_1^c and M_2^c are shown in Figs. 5 and 6, respectively:

$$\begin{aligned}M_1^c=&\frac{ieG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_1)^{1/2}}\,\bar{u}(p_{\nu'})(1-\gamma_5)(\not{p}_{\nu'}-\not{p}+\not{k}_1)\frac{i(\not{p}-\not{k}_1)-m}{(p-k_1)^2+m^2}\not{\epsilon}_1u(p)\\&+\frac{eG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_1)^{1/2}}\,\frac{(k_1+2p_{\nu'}-2p)\cdot\epsilon_1}{(p_{\nu'}-p)^2+m_\pi{}^2}\,\bar{u}(p_{\nu'})(1-\gamma_5)(\not{p}_{\nu'}-\not{p})u(p)\\&-\frac{eG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_1)^{1/2}}\,\bar{u}(p_{\nu'})(1-\gamma_5)\not{\epsilon}_1u(p) \;,\end{aligned} \tag{2.16}$$

$$\begin{aligned}M_2^c=&\frac{ieG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_2)^{1/2}}\,\bar{u}(p_{\nu})(1-\gamma_5)(\not{p}_{\nu}-\not{p}+\not{k}_2)\frac{i(\not{p}-\not{k}_2)-m}{(p-k_2)^2+m^2}\not{\epsilon}_2u(p)\\&+\frac{eG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_2)^{1/2}}\,\frac{(k_2+2p_{\nu}-2p)\cdot\epsilon_2}{(p_{\nu}-p)^2+m_\pi{}^2}\,\bar{u}(p_{\nu})(1-\gamma_5)(\not{p}_{\nu}-\not{p})u(p)\\&-\frac{eG'}{\sqrt{2}\,(2\omega_\pi)^{1/2}(2\omega_2)^{1/2}}\,\bar{u}(p_{\nu})(1-\gamma_5)\not{\epsilon}_2u(p) \;.\end{aligned} \tag{2.17}$$

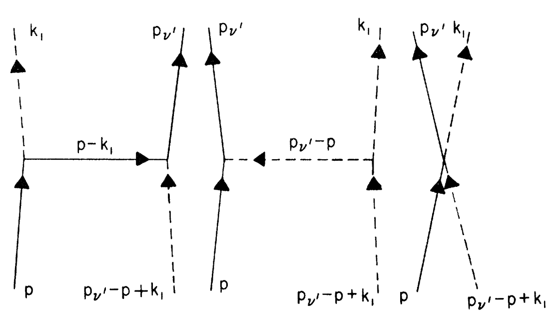

FIG. 5. Graphs for M_1^c.

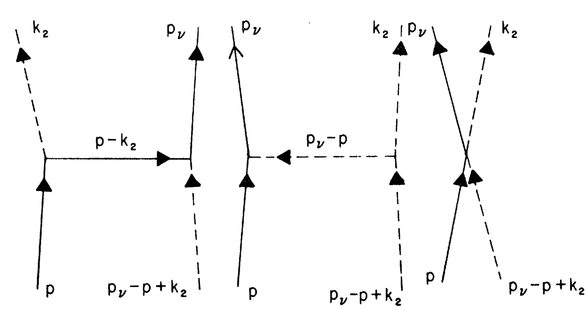

FIG. 6. Graphs for M_2^c.

Let the plane of scattering be the x-z plane, and we choose the center-of-mass frame. Then, in the direct channel, we have

$$\begin{aligned} k_1 &= (0, 0, k, i\omega) , \\ k_2 &= (0, 0 - k, i\omega) , \\ p_\nu &= ((1 - z^2)^{1/2}k, 0, zk, i\omega) , \\ p_{\bar{\nu}} &= (-(1 - z^2)^{1/2}k, 0, -zk, i\omega) . \end{aligned} \tag{2.18}$$

In the crossed channel,

$$\begin{aligned} k_1 &= (0, 0, k, i\omega) , \\ p_{\nu'} &= (0, 0, -k, i\omega) , \\ p_\nu &= ((1 - z^2)^{1/2}k, 0, zk, i\omega) , \\ k_2 &= (-(1 - z^2)^{1/2}k, 0, -zk, i\omega) . \end{aligned} \tag{2.19}$$

In the above equations,

$$z = \cos\theta , \tag{2.20}$$

where θ is the center-of-mass scattering angle.

We also specify our calculation to be in the transverse gauge. Hence, in the direct channel one has the following four linear polarization cases.

$$\begin{aligned} &\text{Case I: } \epsilon_1 = (0, 1, 0, 0), \quad \epsilon_2 = (0, 1, 0, 0) . \\ &\text{Case II: } \epsilon_1 = (1, 0, 0, 0), \quad \epsilon_2 = (-1, 0, 0, 0) . \\ &\text{Case III: } \epsilon_1 = (0, 1, 0, 0), \quad \epsilon_2 = (-1, 0, 0, 0) . \\ &\text{Case IV: } \epsilon_1 = (1, 0, 0, 0), \quad \epsilon_2 = (0, 1, 0, 0) . \end{aligned} \tag{2.21}$$

In the crossed channel, one has the following four linear polarization cases:

$$\begin{aligned} &\text{Case I: } \epsilon_1 = (0, 1, 0, 0), \quad \epsilon_2 = (0, 1, 0, 0) . \\ &\text{Case II: } \epsilon_1 = (1, 0, 0, 0), \quad \epsilon_2 = (-z, 0, (1 - z^2)^{1/2}, 0) . \\ &\text{Case III: } \epsilon_1 = (0, 1, 0, 0), \quad \epsilon_2 = (-z, 0, (1 - z^2)^{1/2}, 0) . \\ &\text{Case IV: } \epsilon_1 = (1, 0, 0, 0), \quad \epsilon_2 = (0, 1, 0, 0) . \end{aligned} \tag{2.22}$$

III. EVALUATION

Expressing the matrix element as

$$M = \sum_i \alpha_i(s, t, u)\beta_i , \tag{3.1}$$

where $\alpha_i(s, t, u)$ is the ith amplitude and β_i is the corresponding ith basis, the process $\gamma + \gamma \to \nu + \bar{\nu}$ can be represented by[2]

$$M = A(s, t, u)\beta_A + B(s, t, u)\beta_B + C(s, t, u)\beta_C . \tag{3.2}$$

The variables s, t, and u are

$$\begin{aligned} s &= -(k_1 + k_2)^2 , \\ t &= -(k_1 - k_3)^2 , \\ u &= -(k_1 - k_4)^2 . \end{aligned} \tag{3.3}$$

The respective bases are

$$\begin{aligned} \beta_A = \bar{u}(p_\nu)\frac{1-\gamma_5}{2}\,[K^2(\not\epsilon_1 P \cdot \epsilon_2 + \not\epsilon_2 P \cdot \epsilon_1) - (P \cdot K)(\not\epsilon_1 K \cdot \epsilon_2 + \not\epsilon_2 K \cdot \epsilon_1) \\ - \not K(K \cdot \epsilon_1 P \cdot \epsilon_2 + P \cdot \epsilon_1 K \cdot \epsilon_2) + P \cdot K \epsilon_1 \cdot \epsilon_2 \not K]\frac{1+\gamma_5}{2}\, v(-p_{\bar{\nu}}) , \end{aligned} \tag{3.4}$$

$$\beta_B = 4(F^1_{\mu\nu}F^2_{\alpha\mu}P_\alpha k^2_\rho k^2_\nu + F^1_{\mu\nu}F^2_{\nu\beta}P_\mu k^1_\rho k^1_\beta)\bar{u}(p_\nu)\frac{1-\gamma_5}{2}\gamma_\rho\frac{1+\gamma_5}{2}\, v(-p_{\bar{\nu}}) , \tag{3.5}$$

$$\beta_C = 2F^1_{\mu\nu}F^2_{\alpha\beta}(P_\mu k^1_\rho \epsilon_{\alpha\nu\beta\sigma}P_\sigma + P_\alpha k^2_\rho \epsilon_{\mu\beta\nu\sigma}P_\sigma)\bar{u}(p_\nu)\frac{1-\gamma_5}{2}\gamma_\rho\frac{1+\gamma_5}{2}\, v(-p_{\bar{\nu}}) , \tag{3.6}$$

where

$$K = k_1 - k_2 , \quad P = p_\nu - p_{\bar{\nu}} . \tag{3.7}$$

Only the basis β_A is of order ω^3, the others being of order ω^5. Hence, to lowest order, we have

$$M \cong A(s, t, u)\beta_A . \tag{3.8}$$

The respective direct- and crossed-channel contributions to $A(s, t, u)$ are[2]

$$A(s, t) = \frac{M_{\mathrm{I}} + M_{\mathrm{II}}}{2\beta_A} , \tag{3.9}$$

$$A(u, t) = \frac{M^c_{\mathrm{I}} + M^c_{\mathrm{II}}}{2\beta'_A} , \tag{3.10}$$

where the indices I and II signify the polarization cases in the respective channels. In Eq. (3.10), we have

$$\beta_A'=\bar u(p_\nu)\frac{1-\gamma_5}{2}\,[K'^2(\not\epsilon_1 P'\cdot\epsilon_2+\not\epsilon_2 P'\cdot\epsilon_1)-(P'\cdot K')(\not\epsilon_1 K'\cdot\epsilon_2+\not\epsilon_2 K'\cdot\epsilon_1)$$
$$-\not K'(K'\cdot\epsilon_1 P'\cdot\epsilon_2+P'\cdot\epsilon_1 K'\cdot\epsilon_2)+P'\cdot K'\epsilon_1\cdot\epsilon_2\not K']\frac{1+\gamma_5}{2}\,u(p_{\nu'})\,, \quad (3.11)$$

where

$$K'=k_1+k_2\,,\quad P'=p_\nu+p_{\nu'}\ . \quad (3.12)$$

The absorptive parts $A'(s,t)$ and $A'(u,t)$ are obtained by substituting the respective channel absorptive parts of M, as given by expressions (2.4) and (2.13).

$$A'(s,t)=\frac{A(T)_{\rm I}+A(T)_{\rm II}}{2\beta_A}\,, \quad (3.13)$$

$$A'(u,t)=\frac{A^c(T)_{\rm I}+A^c(T)_{\rm II}}{2\beta_A'}\ . \quad (3.14)$$

The respective dispersive parts of the amplitudes are obtained from the absorptive expressions by integration:

$$A(s,t)=\frac{1}{\pi}\int_{4m_l^2}^{\infty}\frac{A'(s',t)}{s'-s}\,ds'\,, \quad (3.15)$$

$$A(u,t)=\frac{1}{\pi}\int_{(m_\pi+m_l)^2}^{\infty}\frac{A'(u',t)}{u'-u}\,du'\ . \quad (3.16)$$

The resulting expression for $A(s,t,u)$ is[4]

$$A(s,t,u)=(4.42)\frac{ie^2G'^2}{32\pi^2}\,\frac{m_e^2}{m_\pi^4}\quad\text{electron-type neutrinos}, \quad (3.17)$$

$$A(s,t,u)=(-14.57)\frac{ie^2G'^2}{32\pi^2}\,\frac{m_\mu^2}{m_\pi^4}\quad\text{muon-type neutrinos}. \quad (3.18)$$

In the factor (4.42) appearing in Eq. (3.17), the contribution from the crossed channel is only (0.08). In the factor (−14.57) of Eq. (3.18), the crossed-channel contribution is only (0.15). Thus, for both types of neutrino emission the crossed-channel contributions are very small. The corresponding expression for R is

$$R=\frac{\pi^2e^2G'^2\rho}{2(2\omega_1)^{1/2}(2\omega_2)^{1/2}m_\pi^4}\,\delta(p_\nu+p_{\bar\nu}-k_1-k_2)\bar u(p_\nu)\frac{1-\gamma_5}{2}$$
$$\times[K^2(\not\epsilon_1 P\cdot\epsilon_2+\not\epsilon_2 P\cdot\epsilon_1)-(P\cdot K)(\not\epsilon_1 K\cdot\epsilon_2+\not\epsilon_2 K\cdot\epsilon_1)-\not K(K\cdot\epsilon_1 P\cdot\epsilon_2+P\cdot\epsilon_1 K\cdot\epsilon_2)+P\cdot K\epsilon_1\cdot\epsilon_2\not K]$$
$$\times\frac{1+\gamma_5}{2}\,v(-p_{\bar\nu})\,, \quad (3.19)$$

where

$$\rho=4.42m_e^2\quad\text{electron-type neutrinos}, \quad (3.20)$$

$$\rho=-14.57m_\mu^2\quad\text{muon-type neutrinos}. \quad (3.21)$$

IV. CROSS SECTION AND LUMINOSITY

The unpolarized differential cross section obtained from Eq. (3.19) is

$$\frac{d\sigma}{d\Omega}=\frac{e^4G'^4\rho^2}{2048\pi^6m_\pi^8}\,\omega^6(1-\cos^4\theta)\ . \quad (4.1)$$

The total unpolarized cross section is

$$\sigma=\frac{e^4G'^4\rho^2}{640\pi^5m_\pi^8}\,\omega^6\ . \quad (4.2)$$

Evaluating Eq. (4.2), one obtains

$$\sigma=5.4\times10^{-64}\left(\frac{\omega}{M_p}\right)^6\text{cm}^2$$

electron-type neutrinos, (4.3)

$$\sigma=1.1\times10^{-53}\left(\frac{\omega}{M_p}\right)^6\text{cm}^2$$

muon-type neutrinos. (4.4)

TABLE I. Neutrino cross sections and luminosities for various intermediate-boson masses. The units of σ and L are cm^2 and $\mathrm{erg/cm^3\,sec}$, respectively.

	$\sigma(\nu_e, \bar{\nu}_e)$	$\sigma(\nu_\mu, \bar{\nu}_\mu)$	$L(\nu_e, \bar{\nu}_e)$	$L(\nu_\mu, \bar{\nu}_\mu)$
$M_W = 10$ GeV	$1.9\times 10^{-46}(\omega/M_p)^6$	$3.5\times 10^{-47}(\omega/M_p)^6$	$8.1\times 10^{-8}(T/10^9)^{13}$	$1.5\times 10^{-8}(T/10^9)^{13}$
$M_W = 50$ GeV	$4.1\times 10^{-49}(\omega/M_p)^6$	$1.1\times 10^{-49}(\omega/M_p)^6$	$1.8\times 10^{-10}(T/10^9)^{13}$	$4.7\times 10^{-11}(T/10^9)^{13}$
$M_W = 100$ GeV	$2.9\times 10^{-50}(\omega/M_p)^6$	$8.5\times 10^{-51}(\omega/M_p)^6$	$1.2\times 10^{-11}(T/10^9)^{13}$	$3.7\times 10^{-12}(T/10^9)^{13}$
$M_W = 500$ GeV	$5.9\times 10^{-53}(\omega/M_p)^6$	$2.1\times 10^{-53}(\omega/M_p)^6$	$2.6\times 10^{-1}(T/10^{10})^{13}$	$9.3\times 10^{-2}(T/10^{10})^{13}$
$M_W = 1000$ GeV	$4.1\times 10^{-54}(\omega/M_p)^6$	$1.6\times 10^{-54}(\omega/M_p)^6$	$1.8\times 10^{-2}(T/10^{10})^{13}$	$6.9\times 10^{-3}(T/10^{10})^{13}$

The corresponding blackbody neutrino luminosities are

$$L = 2.4\times 10^{-12}\left(\frac{T}{10^{10}}\right)^{13}\ \mathrm{erg/cm^3\,sec}$$

electron-type neutrinos, (4.5)

$$L = 4.7\times 10^{-2}\left(\frac{T}{10^{10}}\right)^{13}\ \mathrm{erg/cm^3\,sec}$$

muon-type neutrinos. (4.6)

In Ref. 2, the expression obtained for σ is

$$\sigma = \frac{e^4 g^4}{160\pi^5 M_W{}^8}\left(\tfrac{1}{3}\ln\frac{M_W{}^2}{m^2} - \tfrac{23}{72}\right)^2 \omega^6 . \tag{4.7}$$

Table I gives the corresponding values of the cross sections and luminosities for various intermediate-boson masses M_W.[5]

Upon comparison, one finds that the expressions for $\sigma(\nu_\mu, \bar{\nu}_\mu)$ and $L(\nu_\mu, \bar{\nu}_\mu)$ of Eqs. (4.4) and (4.6) are of the order of magnitude of $\sigma(\nu_e, \bar{\nu}_e)$ and $L(\nu_e, \bar{\nu}_e)$ of Ref. 2 for $M_W = 500$ GeV. Of particular interest is to note that in Ref. 2 the respective expressions for σ and L are always greater for electron-type neutrino emission, whereas those of Eqs. (4.3)–(4.6) are greater for muon-type emission.

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[4]See the Appendix of Ref. 2 for the methods of approximation employed.
[5]A factor of $(4\pi)^2$ was omitted from the respective expressions for $M_W = 2$ GeV in Ref. 2.