Finite-size corrections to Fermi's golden rule: Implications to neutrino physics

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References:

(1)K.Ishikawa and Y.Tobita,P.T.E.P;073 (2013) B02,

(2)K.I and Y.Tobita , Annals of Physics ,344 (2014), 118-178

(3)K.I,T.Nozaki,M.Sentoku,and Y.Tobita, arXiv:1405.0582[hep-ph]

(4)K.I, T.Tajima, and Y.Tobita, arXiv:1409.4339[hep-ph]

(5)K.I and Shimomura,PTP(2005), and others

$Contents$

$The\ probability\ of\ the\ event\ is\ computed\ in\ Quantum\ mechanics$

$The\ event\ is\ specified\ by\ the\ initial\ state\ and\ final\ states$

$The\ states\ are\ expressed\ by\ the\ boundary\ conditions$

$$i\hbar \frac{\partial}{\partial t} \Psi(t, \vec{x}) = (H_0 + H_{int}) \Psi(t, \vec{x})$$

1-1. Transition rate at T is computed with the amplitude,

Large T

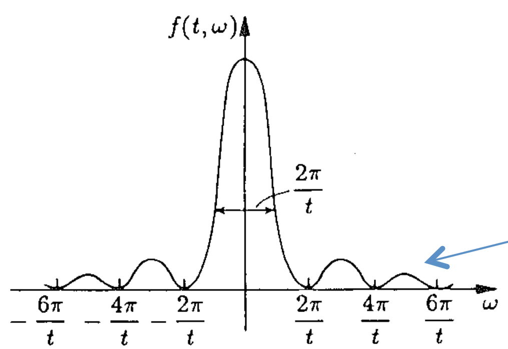
$$\int_0^T dt e^{i\omega t} = \frac{1}{i\omega}(e^{i\omega T} - 1) = e^{i\omega T/2}\frac{2\sin\omega T/2}{\omega}$$

$$P = g^2 \int d\omega (\frac{2\sin\omega T/2}{\omega})^2 |f_{\alpha,\beta}|^2$$

$$= g^2 T \int dx (\frac{2\sin x}{x})^2 [g(0) + \frac{x}{T} g'(0) + \cdots]$$

$$= g^2 2\pi T g(0)[1 + \frac{1}{T} \times \infty + \cdots],$$

$$x = \omega T/2, g = |f_{\alpha,\beta}|^2 \qquad \omega = (E_i - E_f)/\hbar$$



11.8：関数 $f(t,\omega)$ は $t\to\infty$ において $2\pi t\delta(\omega)$ となる．すなわち $\omega=0$ のピークは鋭く
る．

1.Amplitude at Large T is determined by the states of

$$\omega \approx 0 \qquad P = T\Gamma_0$$

Golden rule (Dirac(1927),Fermi(1949))

2. (1)1/Tcorrection？

(2) If g(0)=0, ?

$$P = T(\Gamma_0 + \frac{P^{(d)}}{T})$$

Tails give 1/T corrections

Kinetic-energy non-conservation

$$E_k = E_{total} - E_{int} \neq E_{total}, \text{ for } E_{int} \neq 0$$

1-2. Transition probability P (of time interval T)

$$P = T\Gamma_0 + P^{(d)} \quad : T - linear \ + \ constant$$

$\Gamma_0 : Fermi's\ golden\ rule$

$P^{(d)} : correction$ (our work)

1-1. $P^{(d)}$ *is very different from* Γ_0

$\Gamma_0 : particle - like \ behavior \ (\nu \ flavor \ oscillation)$

$P^{(d)} : wave - like \ behavior \ (\nu \ diffraction)$

1-2. $P^{(d)}$ has been ignored in most places,
but affects the transtions of non-stationary waves. .

1-3. $P^{(d)}$ is important in ν , γ reactions

2 .Quantum Field Theory

$$L = \bar{\psi}\gamma_\mu(p^\mu + eA^\mu)\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}(QED), or L(QFD)$$
$$+Higgs$$

Symmetry: Poincare Invariance

Conserved quantities: Energy- momentum, angular momentum, and others

Boundary conditions

1. Vacuum and excitations follow Poincare invariance

$$|0\rangle, \quad |p_i\rangle, \quad |p_{i_1}, p_{i_2}\rangle, \cdots$$

2. In matter, matter effects, detector effects(many –body effects) would violate some invariance and be different.

3. In scattering or decays, boundary conditions are important

$S[T]\ is\ constructed\ with\ LSZ(1955)\ formula$

$$lim_{t\to\pm T/2}\langle\alpha|\phi^f(t)|\beta\rangle = \langle\alpha|\phi^f_{in}|\beta\rangle$$

$$\phi^f(t) = i\int d^3x f^*(\vec{x},t)\partial_0\phi(\vec{x},t)$$

$$S[T] = \Omega_-^\dagger(T)\Omega_+(T)$$

$$\Omega_\pm(T) = lim_{t\to\mp T/2}U(t)^\dagger U_0(t)$$

$$S[T]S^\dagger[T] = 1$$

$$\langle\alpha|S[T]|\beta\rangle = \langle\alpha|S^n[T]|\beta\rangle + \langle\alpha|S^{(d)}[T,f]|\beta\rangle$$

$$E_\alpha = E_\beta, \qquad E_\alpha \neq E_\beta$$

$$T\Gamma_0, \qquad P^{(d)}$$

wave packet ↓

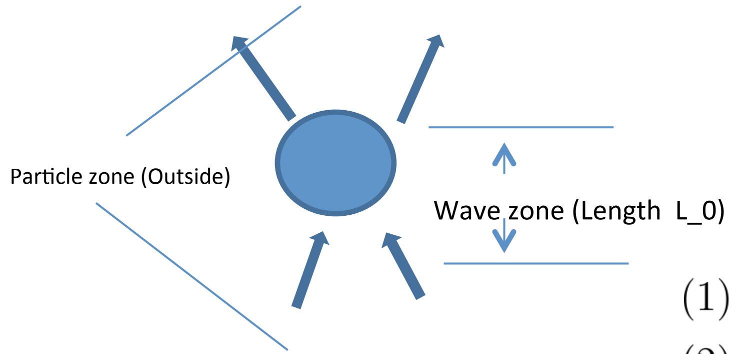
(1) Boundary conditions at T＝T/2,-T/2、depend on f(x).

(2) Amplitude and probability depend on f（x）.

(3) $f(x;\vec{p},\vec{X},T) = N\int d\vec{k}e^{-\sigma/2(\vec{k}-\vec{p})^2+i(E(\vec{k})(t-T)-\vec{k}(\vec{x}-\vec{X})}, \sigma = nuclear\ size$

(4) Position $\vec{X},T$ and momentum $\vec{p}$ for a complete set.

2-1 Asymptotic states are particles



Pion or charged leptons $S[\infty], L = c \times \infty$

$$P_{pion}(T) = T\Gamma_0$$

$$(1)[S[\infty], H_0] = 0$$

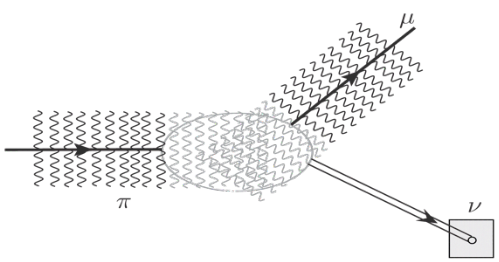
$$(2) Kinetic\ energy\ is\ conserved.\ \ (kinetic\ energy = total\ energy)$$

$$(3) Fermi's\ golden\ rule, S - matrix, e^{-\epsilon|t|}H_{int}$$

2-2. Asymptotic states are waves

$S[T], L = cT$

Amplitude of the events that ν is detected at $(\vec{X}_\nu, T_\nu)$



Waves overlap in large area , and have finite interaction energy

Neutrino phenomena

$$P_\nu(T) = T\Gamma_0 + P^{(d)}$$

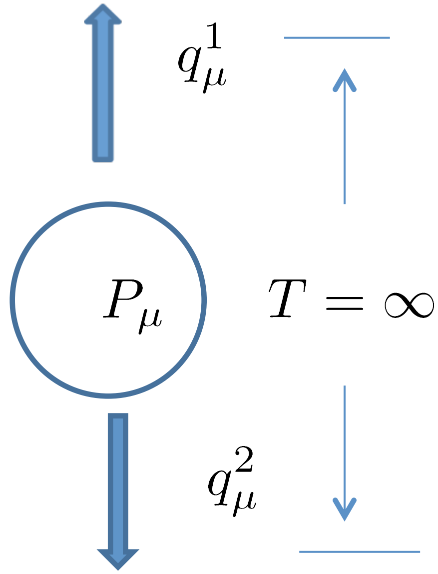
$$(1)\ [S[T], H_0] \neq 0$$

$$(2)\ kinetic\ energy\ non - conservation,$$

$$(3)\ Fermi's\ golden\ rule\ has\ a\ correction$$

$Wave's\ characteristic\ features\ appear\ in\ space - time\ dependece$
$and\ are\ probed\ with\ wave\ packets$

Particle-like behavior; no-overlap

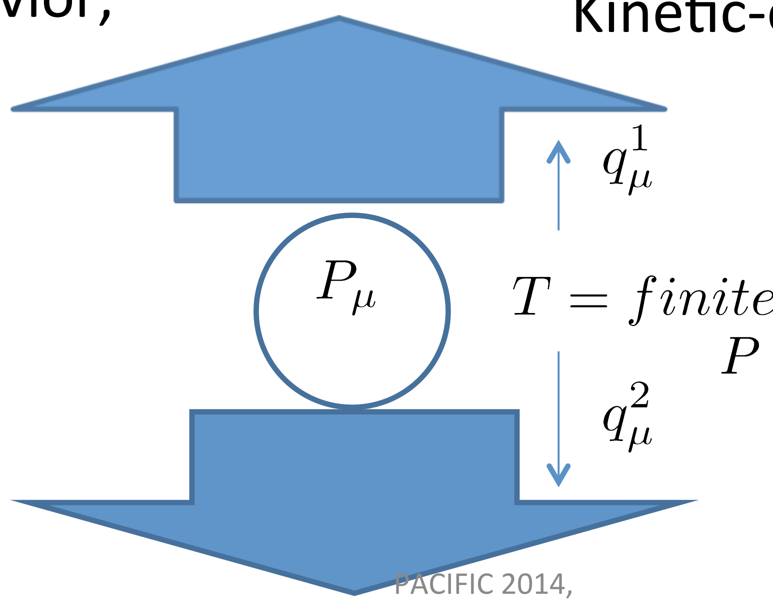


Kinetic-energy conserved

$$P_\mu = q_\mu^1 + q_\mu^2$$

$$P = \Gamma_0 T$$

Wave-like behavior; overlap



Kinetic-energy non-conservation

$$P_\mu \neq q_\mu^1 + q_\mu^2$$

$$P = P^{(d)} + T\Gamma_0$$

3. Pion decay amplitude : neutrino is detected at L=cT $S[T]$

- By using wave packets, probability amplitude of the event is given [LSZ]. ν

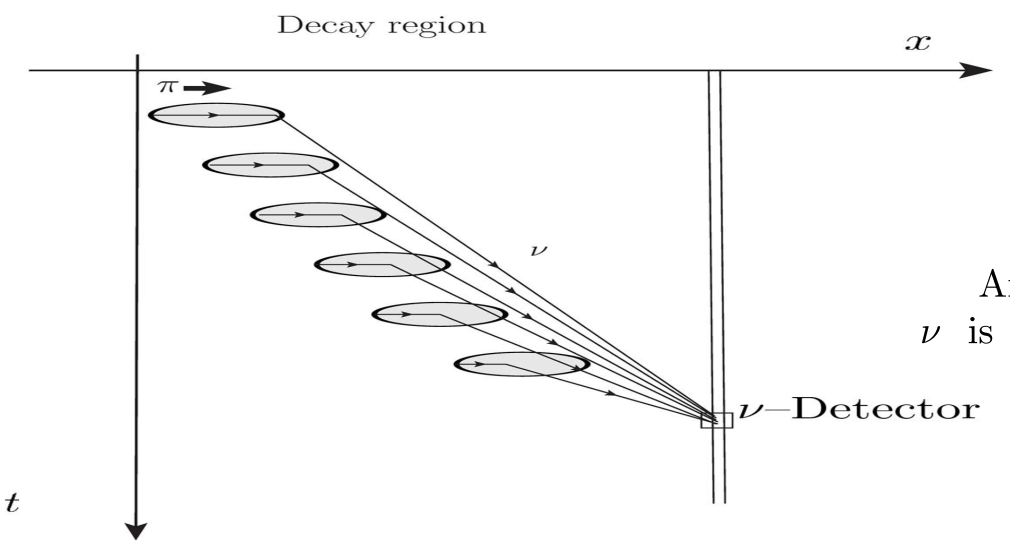
*P^{(d)} is caused by the kinetic-energy non-conserving term .

$$\bar{\mathrm{M}} = \int d^4x \langle l,\nu|H_w(x)|\pi\rangle$$
$$= \int d^4x N_1 \langle 0|J^{\mu}_{V-A}|\pi\rangle \bar{u}(\vec{p}_l)\gamma_\mu(1-\gamma_5)\nu(p_\nu)e^{ip_l\cdot x+ip_\nu\cdot(x-\mathrm{X}_\nu)}e^{-\frac{1}{2\sigma_\nu}\left(\vec{x}-\vec{\mathrm{X}}_\nu-\vec{v}_\nu(t-\mathrm{T}_\nu)\right)^2}$$

$\vec{v}_\nu$ is large

Neutrino velocity

important (moving frame)

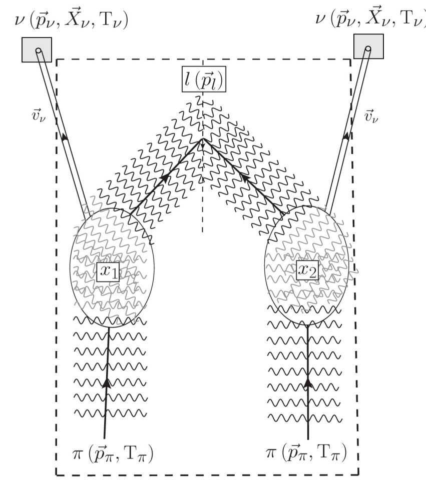


Amplitude of the events that ν is detected at $(\vec{X}_\nu, T_\nu)$

Rigorous calculation : light-cone singularity+short- range

$$\int \frac{d^3p_l}{(2\pi)^3}\sum_{spin}|T|^2 = \frac{N_3}{E_\nu}\int d^4x_1 d^4x_2 e^{-\frac{1}{2\sigma_\nu}\sum_i(\vec{x}_i-\vec{X}_\nu-\vec{v}_\nu(t_i-T_\nu))^2}$$
$$\times \Delta_{\pi,l}(x_1-x_2)e^{ip_\nu\cdot(x_1-x_2)}$$
$$\Delta_{\pi,l}(x_1-x_2)=\frac{1}{(2\pi)^3}\int\frac{d^3p_l}{E(p_l)}\left[(2p_\pi\cdot p_\nu)(p_\pi\cdot p_l)-m_\pi^2(p_l\cdot p_\nu)\right]$$
$$\times e^{-i(p_\pi-p_l)\cdot(x_1-x_2)}$$
$$=\delta((x_1-x_2)^2)+short-range$$

ν M



Light-cone singularity

$$e^{ip_\nu(x_1-x_2)}\delta((x_1-x_2)^2)=e^{i(E_\nu-p_\nu)(x_1-x_2)^0}=e^{i\frac{m^2}{2E}(x_1^0-x_2^0)}\rightarrow P^{(d)}$$

$$e^{ip_\nu(x_1-x_2)}\times(short-range)\rightarrow T\Gamma_0$$

ν v_ν large and $\approx constant$ small $\frac{m^2}{2E}$

$$P_\nu(T)=T\Gamma_0+P^{(d)}$$
$$P^{(d)}=CT\tilde{g}\left(\frac{m_\nu^2T}{2E_\nu}\right)\approx C\frac{2E_\nu}{m_\nu^2}(macro.T),\tilde{g}(0)=\pi$$

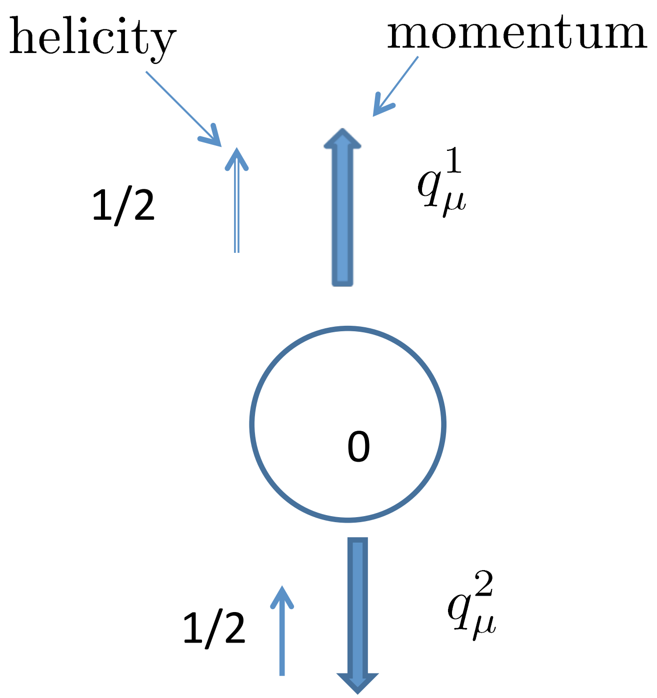
charged leptons or pion large $\frac{m^2}{2E}$

v_l small *and* varies

$$P=T\Gamma_0$$

energy scale: $\frac{(m_\nu c^2)^2}{E_\nu}$

Light fermion

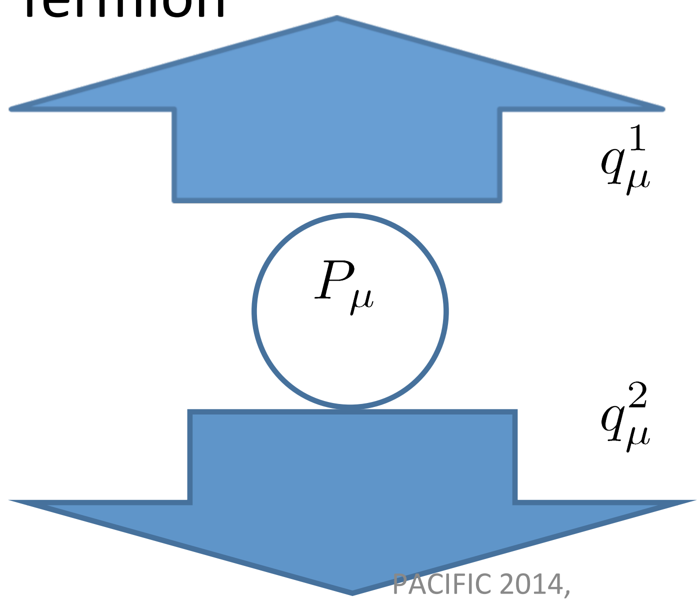


Forbidden for m_l=0
Ruderman-Finkelstein-, Steinberger,
Sasaki-et al,-('49) .

$$\Gamma_0 = 0$$

$$H_w = (V - A)_\mu (V - A)^\mu$$

Waves of light fermion



Allowed $(KI\ and\ YT)$

$$P^{(d)} \neq 0$$

$$P_\mu \neq q_\mu^1 + q_\mu^2$$

$$0^- \to l + \nu_l \qquad P = T\Gamma_0(l,\nu_l) + P^{(d)}(l,\nu_l)$$

(I) Helicity suppression due to V-A interaction

$(1)\Gamma_0(l,\nu_l) = m_l^2 C_0 \approx 0 \ (l = e)$

$(2)\Gamma_0(e,\nu_e)/\Gamma_0(\mu,\nu_\mu) = 10^{-4}$

(II) Unique properties of $P^{(d)}(l,\nu_l))|_{observed\ particle}$

(1) depends on observed particle; $P^{(d)}(e,\nu_e)|_{\nu_e} \neq P^{(d)}(e,\nu_e)|_e$

(2)hold universality. $P^{(d)}(e,\nu_e)|_{\nu_e} = P^{(d)}(\mu,\nu_\mu)|_{\nu_\mu}$

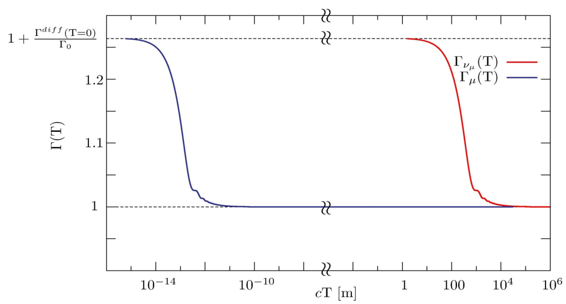
(3)$P^{(d)}$ depends on absolute neutrino mass, m_ν.

$$P^{(d)} = \frac{8}{15} g^2 m_\pi^4 (1 - \frac{m_l^2}{m_\pi^2})^4 (1 + \frac{3m_l^2}{m_\pi^2}) \frac{m_\pi^2 \sigma_l p_\pi}{m_l^2}$$

$l : lepton\ or\ \nu \qquad Due\ to\ \frac{1}{m_l^2}, large\ symmetry\ breaking$

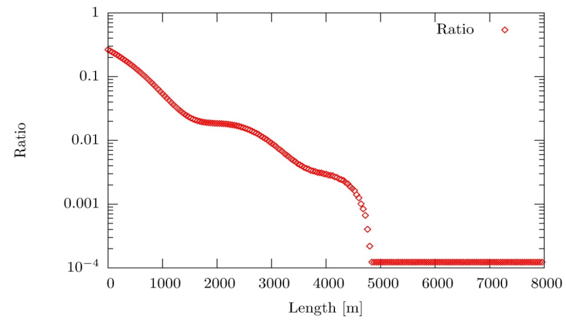
Include τ_π

$\mathrm{R}ate(\nu, \mathrm{T})$ vs $\mathrm{R}ate(\mu, \mathrm{T})$



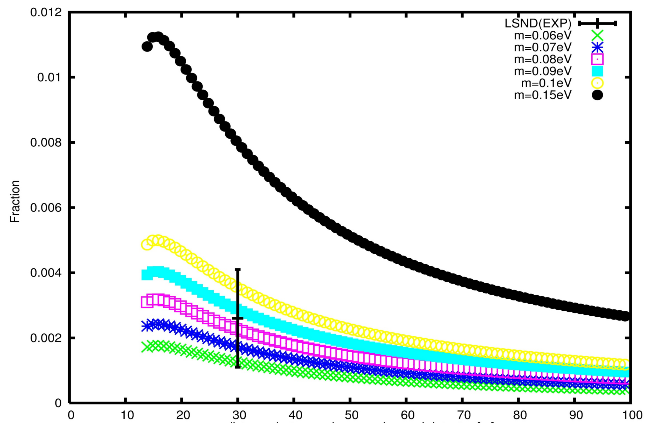
$L = cT$

$\mathrm{R}ate(\nu_e)/\mathrm{R}ate(\nu_\mu)$



$L = cT$

$Exp.$ $\nu_e(LSND)$ vs m_ν P_{ν_e}/P_{ν_μ}



$L = cT$

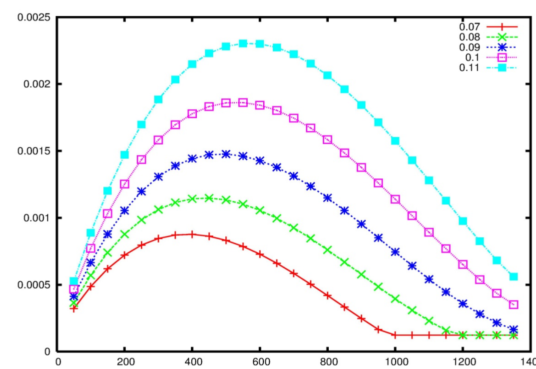
$$\frac{\hbar}{\tau_\pi} \approx \frac{m_\nu^2}{E_\nu}, sensitive\ to\ m_\nu$$

$m_{\nu_l} = 0.085 \pm 0.022 eV/c^2, m_{\nu_h} = 0.098 \pm 0.022, eV/c^2;$ *normal hierarchies*

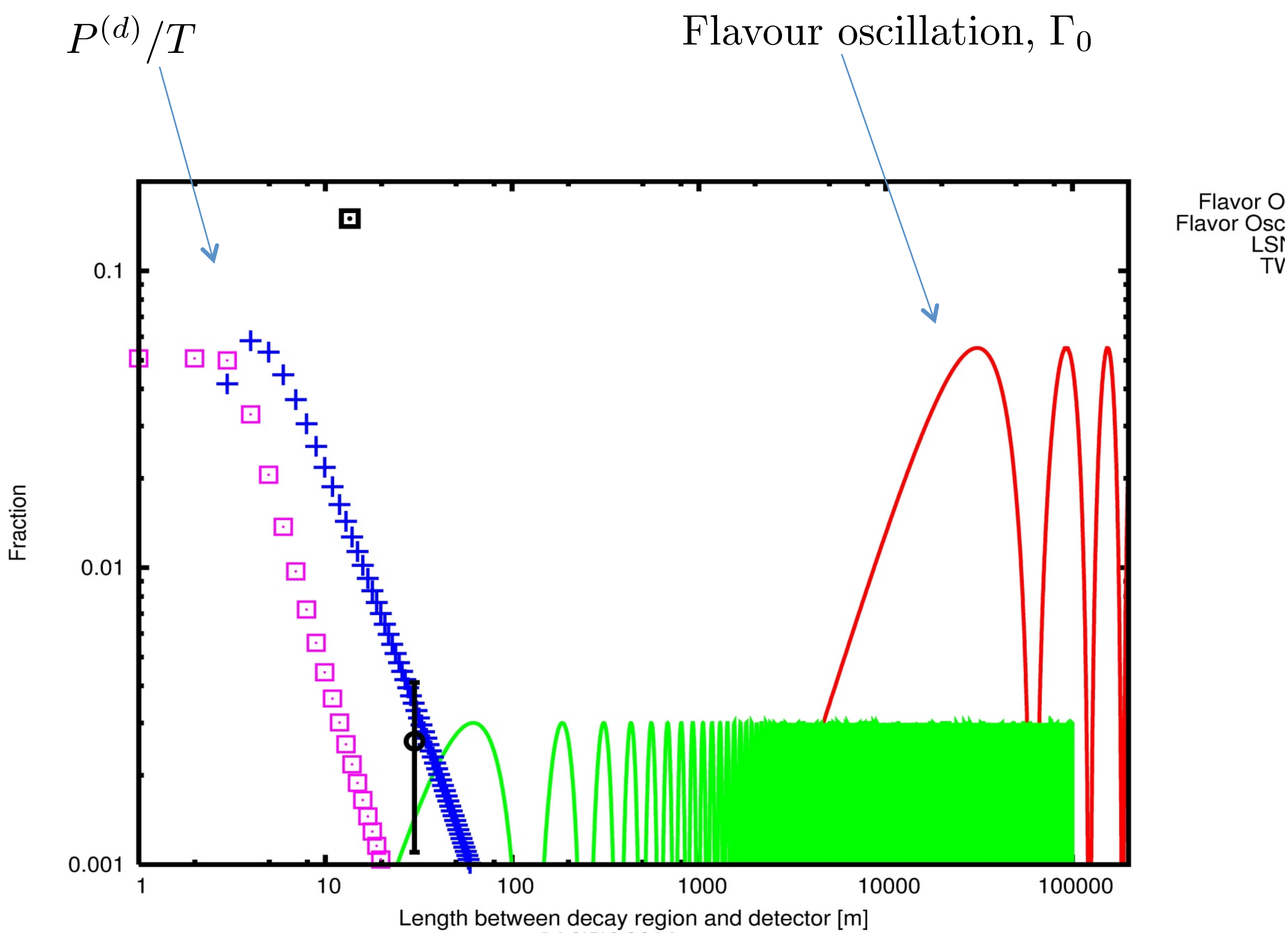
$m_{\nu_l} = 0.070 \pm 0.026 eV/c^2, m_{\nu_h} = 0.083 \pm 0.026 eV/c^2;$ *inverted hiearchies*

Absolute neutrino mass (LSND)

ν_e appearance at near detector(T2K)



L_{decay-detector} = 170[m],
•axis = 2.5 degree,
Detector 3[m]x3[m]



$P^{(d)}/T$
Flavour oscillation, Γ_0
Flavor O
Flavor Osc
LSI
TV
0.1
0.01
0.001
Fraction
1
10
100
1000
10000
100000
Length between decay region and detector [m]

$3 - 2. Muon\ decay\ (Ishikawa - Nozaki - Sentoku - Tobita)$

$$\mu \rightarrow \bar{\nu}_e + e + \nu_\mu$$

$$Lehman's\ spectrum\ representation\ \rho(m^2)\ for\ (e\ and\ \nu_\mu)$$

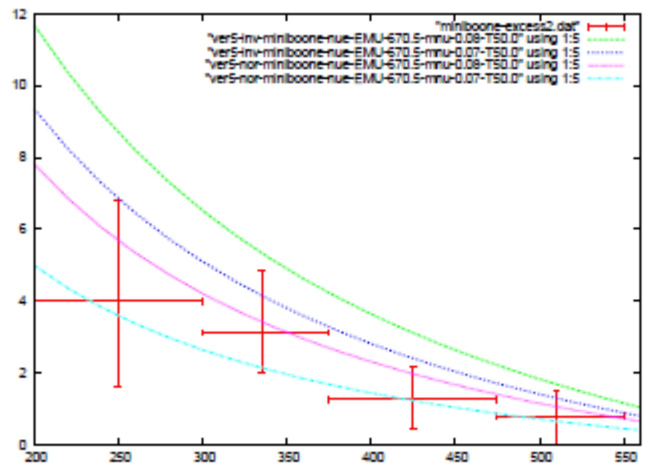
$$P^{(d)} = \frac{2G_F^2}{(2\pi)^3 E_\mu} \int \frac{d\vec{p}_{\nu_e}}{(2\pi)^3 E_{\nu_e}} 2\pi p_\mu \cdot p_{\nu_e} \int dm^2 \rho(m^2) [\sigma_{\nu_e} C \tilde{g}(\omega_{\nu_e}, T; \tau_\mu) + "Normal"]$$

$LSND, KARMEN, MiniBooNE, decay\ in\ flight: \Gamma_0$

$LSND, MiniBoone, decay\ at\ rest. \Gamma_0 + P^{(d)}$

Comparison with Exp.

MiniBooNE



. 5. $P^{(d)}_{\bar{\nu}_e}/P^{(0)}_{\bar{\nu}_e}(\mu)$ is compared with MiniBooNE data including statistic and systematic er-
[16]. For numerical calculation, $m_{\nu_h} = 0.07$ eV (blue: inverted, light blue: normal) ,$m_{\nu_h} =$
eV (green: inverted, magenta: normal), $E_\mu = 670$ MeV, and $E_\pi = 1.15$ GeV are used.

DAR: LSND ,KAEMEN

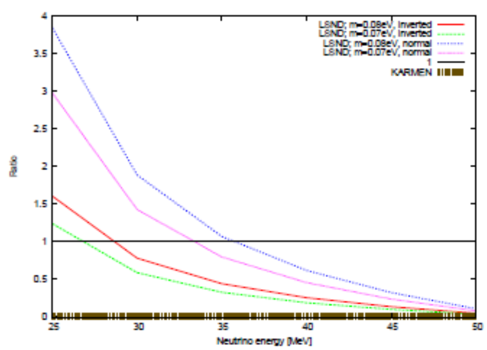


FIG. 8. The ratios $\frac{dP^{(d)}/dE}{dP^{pure}/dE}$ are shown. For LSND, $T_\mu = 0$, $cT = 0.8$m ($T \sim 2.5$ns), $L = 29.8$m, $\sigma^{\rm LSND}_{\bar{\nu}_e}$, $\Delta m^2_{LSND} = 1.2{\rm eV}^2$ and $\sin^2 2\theta_{LSND} = 0.003$ are used. Red curve shows inverted hierarchy of $m_{\nu_h} = 0.08$ eV, green curve shows inverted of $m_{\nu_h} = 0.07$ eV, blue curve shows normal hierarcy of $m_{\nu_h} = 0.08$ eV, and magenta curve shows normal of $m_{\nu_h} = 0.07$ eV. For KARMEN, $T_\mu = 0.3\mu$s, $\Delta t = 5\mu$s, $cT = 0.3$m ($T \sim 1.0$ns), $m_{\nu_h} = 0.08$ eV, $L = 17.7$m, alngle between proton beam and detector $\theta = 100^o$, $\sigma^{\rm KARMEN}_{\bar{\nu}_e}$, $\Delta m^2_{LSND} = 1.2{\rm eV}^2$ and $\sin^2 2\theta_{LSND} = 0.003$ are used. The time resolution T_R is set to 20 ns in both cases. A geometry for μ^+DAR is shown in Fig.7 and a relation between T and θ is given in Appendix.

ν_e *energy spectrum*

$red: \ normal, \quad green: \ P^{(d)}$

$(top) cT = 1\text{meter}:$

$(bottom) cT = 10\text{meter}$

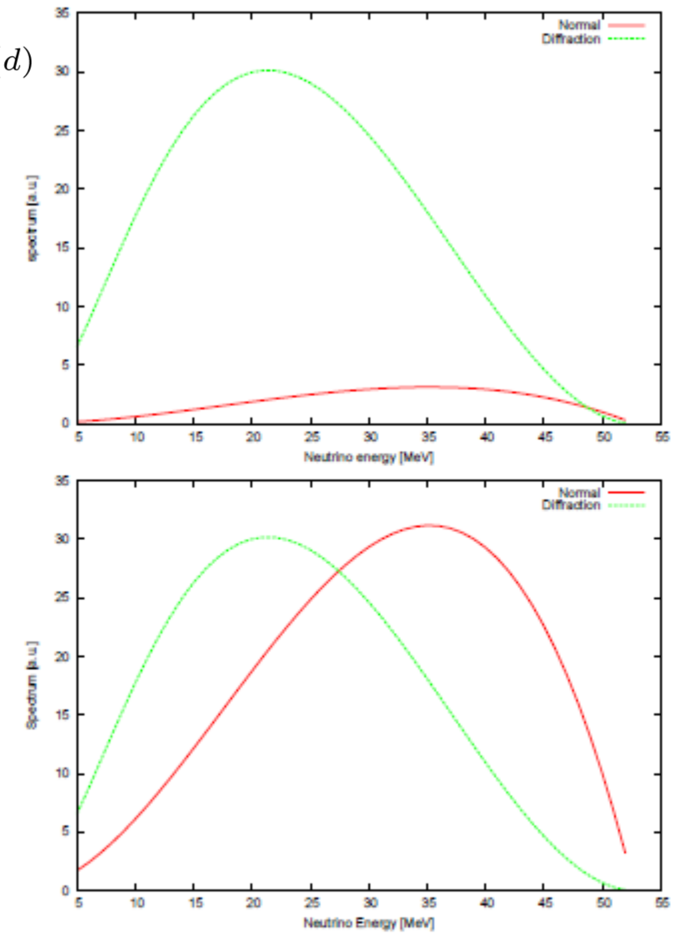


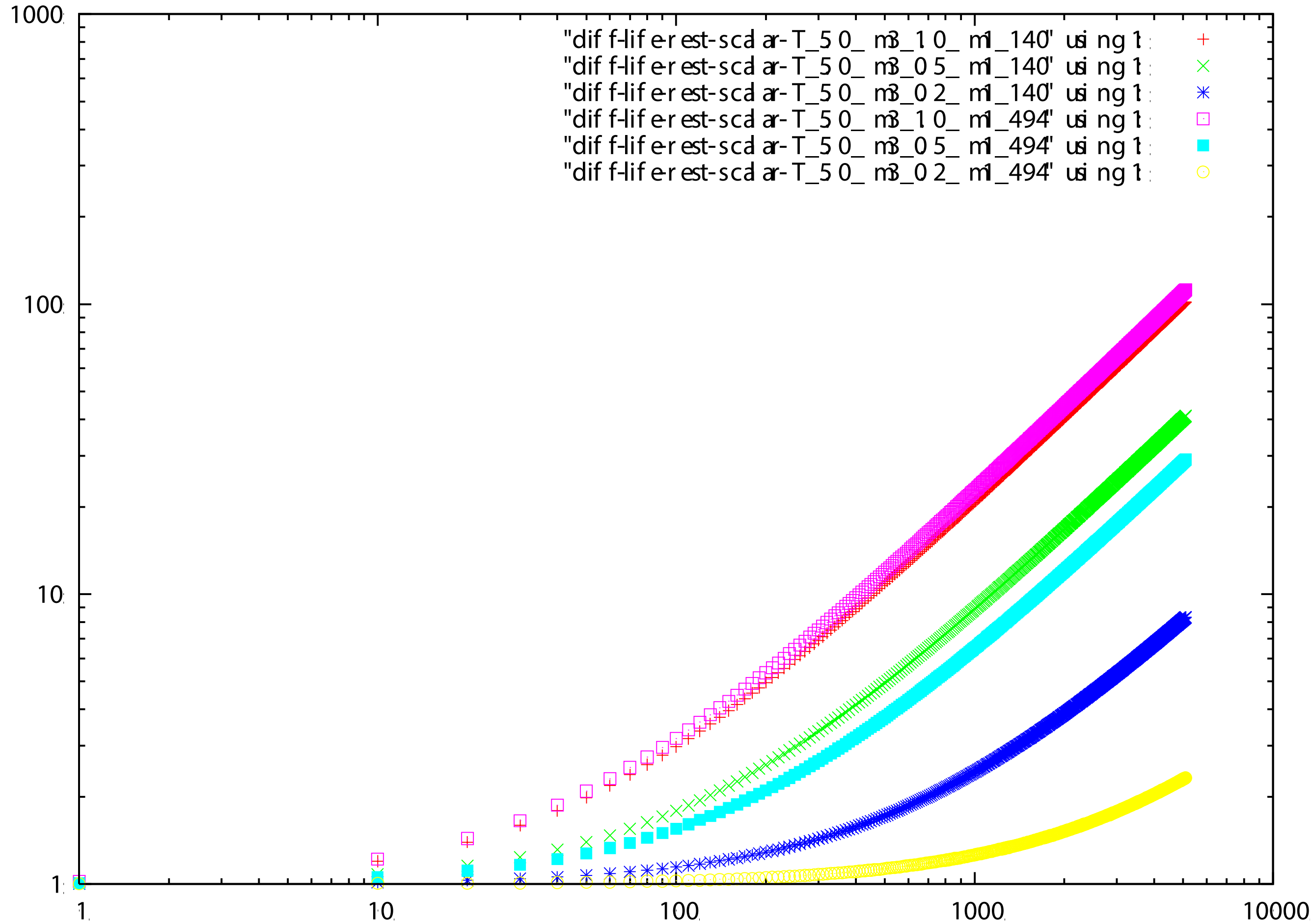
FIG. 3. (Color online) ν_e spectrum in μDAR. The red curve shows normal component given in Eq. (86) and green curve shows diffraction component given in Eq. (85). $m_{\nu_e} = 0.08$ eV, and $2\sigma_{\nu_e} = 12^{\frac{2}{3}}/m_\pi^2$ (^{12}C carbon target) are used for numerical computation. Here, detector is located at $L = 0$. The top figure is for $cT = cT_D = 1$ and bottom one is for $cT = cT_D = 10$ m.

Weak decays: enhancement factor vs size of wave packet σm_π^2

Pi,K decays

$T = 1.7 \times 10^{-8} s$

$\frac{\Gamma_0 + P^{(d)}/T}{\Gamma_0}$



size of wave packet σm_π^2

$P^{(d)}$ causes reactions extended to macroscopic areas:

Differences	Γ_0	$P^{(d)}$
Kinetic energy conservation	*Yes*	*No*
Lorentz invariance	*Yes*	*No*
Particle characteristics	*particle*	*wave*
helicity suppression	*Yes*	*No*
micro vs macro	*micro*	*macro*
λ(*typical length*)	$\frac{\hbar}{p}$	$\frac{\hbar}{mc}\,\frac{E}{mc^2}$
$L_{int} = \frac{d}{dt}G$	$= 0$	$\neq 0$
contributes to natural phenomena	*Yes* +	*Yes*

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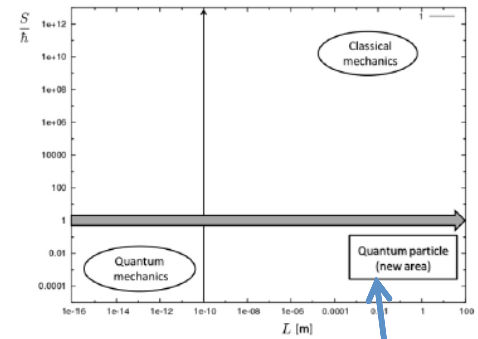
1-1 quantum vs classical
length L vs action S

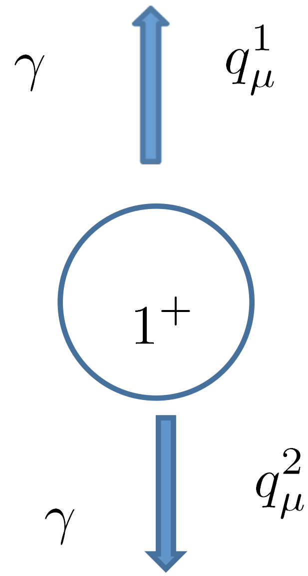


1-2 electron mass and Bohr radius

$$m_e = 0.5 MeV/c^2$$
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = r_e\alpha^{-2} = 0.5 \times 10^{-10} M(Bohr\ radius)$$

A new area of quantum

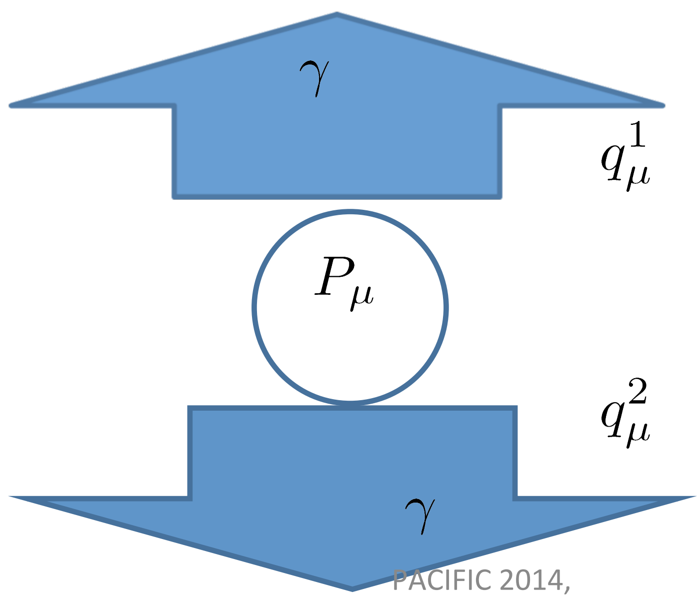
$4.1^+ \; meson(c\,\bar{c}, e^-e^+, \nu\,\bar{\nu}) \rightarrow \gamma\gamma(Ishikawa - Tajima - Tobita)$



$\Gamma_0 = 0$ (Landau-Yang)

$H_{int} = arbitrary$

Wave zone



$P^{(d)} \neq 0$

$P_\mu \neq q_\mu^1 + q_\mu^2$

Landau-Yang's theorem

2photon state $|\gamma, \gamma\rangle$

$$(j_{z1}, j_{z2}) = |+1, +1\rangle,\ |-1, -1\rangle, |+1, -1\ \rangle \pm |-1, +1\rangle$$

$$(J, J_z) = (2, +2),\ \ (2, -2),\ \ \ \ (2, 0),\ \ \pm\ (0, 0)$$

Momentum 1; $(0, 0, p)$
Momentum 2; $(0, 0, -p)$

$$\Gamma_0 = 0\ \ (Landau - Yang)$$

Momentum 1; $(\delta p_1, \delta p_2, p + \delta p_3)$
Momentum 2; $(\delta p'_1, \delta p'_2, -p + \delta p'_3)$

$$P^{(d)} \neq 0$$

$$m_{eff} : photon's\ effective\ mass$$

$$1. In\ vacuum : m_{eff} = 0\ (gauge\ invariance)$$

$$2. In\ matter :$$

$$(2-1 : low\ \omega) \quad n = 1 + \epsilon$$

$$(2-2 : high\ \omega) \quad n = 1 - \frac{\omega_p^2}{\omega^2}$$

$$E(p)^2 = \frac{p^2}{n^2} = p^2 + 2\omega_p^2$$

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e^2}}$$

triangle diagram

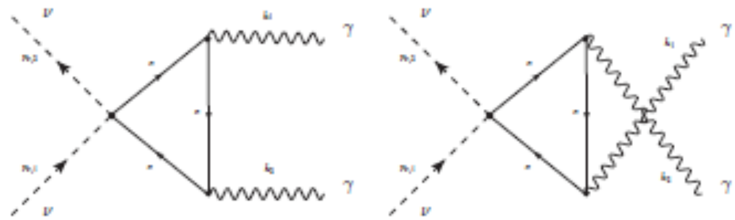


Figure 1: Tri-angle diagram of the electron loop which gives contributions to $1^+(l\bar{l}) \to \gamma\gamma$, $\nu + \gamma \to \nu + \gamma$ and $\nu + \bar{\nu} \to \gamma + \gamma$.

$$\Gamma_{5,\alpha} = \langle 0|J_{5,\alpha}(0)|k_1, k_2\rangle = -i\frac{e^2}{4\pi}2f_1\epsilon^{\mu_1}\epsilon^{\mu_2}$$

$$\times\left[(k_{1,\mu_2}\epsilon\mu_1\nu_1\nu_2\alpha - k_{2,\mu_1}\epsilon_{\mu_2\nu_1\nu_2\alpha})k_1^{\nu_1}k_2^{\nu_2} + (k_1k_2)\epsilon_{\mu_1\mu_2\nu\alpha}(k_1-k_2)^\nu\right]$$

$$f_1 = \frac{1}{4k_1k_2}; k_1k_2 \gg me^2$$

$$= \frac{1}{2m_e^2}; k_1k_2 \ll m_e^2$$

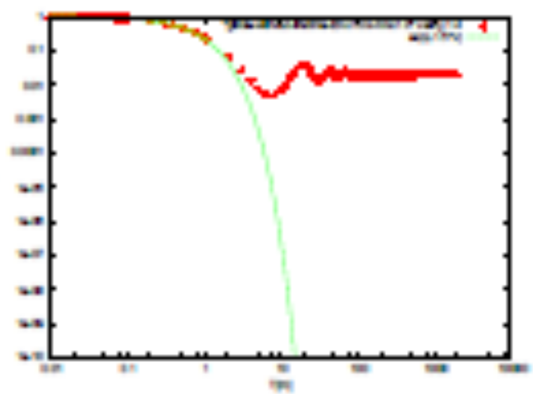
Effective action :axial vector decay $\phi^{\mu} \rightarrow \gamma + \gamma$

$$S_{int} = \int dx \partial_{\mu}(g\phi^{\mu}\epsilon_{\alpha\beta\gamma\delta}F^{\alpha\beta}F^{\gamma\delta})$$
$$= \int_{surface} dS_{\mu} g\phi^{\mu}(x)\epsilon_{\alpha\beta\gamma\delta}F^{\alpha\beta}F^{\gamma\delta}$$

The surface term gives no bulk effect, $\Gamma = 0$, but $P^{(d)} \neq 0$.

$$P = P^{(d)}$$

$$P^{(d)} = \frac{(\pi-2)^2}{1536}\frac{(g\alpha)^2}{4\sqrt{\pi\sigma_{\gamma}}m_{\gamma}^2}\frac{E_c + 2p_c}{E_c(E_c+p_c)}$$



decreases with T as $e^{-T\,\xi(\omega, T)}$

Neutrino light scattering

$$(1)\ \nu+\gamma\ \rightarrow\ \nu+\gamma(\Gamma=0; Gell-Mann(1964))$$

$$Effective\ action$$

$$S_{\nu\gamma}=\frac{\alpha G_F}{2\pi\sqrt{2}}\int d^4x\frac{\partial}{\partial x_\mu}(J^A_\mu\tilde{F}_{\alpha\beta}F^{\alpha\beta})$$

$$J^A_{mu}=\bar{\nu}(x)(1-\gamma_5)\gamma_\mu\nu(x)$$

$$P^{(d)}=\frac{G_F^2\alpha^2}{96\pi^2}\frac{1}{\sqrt{\pi\sigma_\gamma}}\frac{p^2}{m_\gamma^2}; CM\quad high\ energy$$

$$(2)\ \nu+(B,E)\rightarrow\nu+\gamma$$

$$P^{(d)}=\frac{{G_F}^2\alpha}{\pi^2}(\frac{eE(cB)}{m_e c^2})^2\frac{C(m_\nu){p_\nu}^3}{\sqrt{\pi\sigma_\gamma}{m_\gamma}^2{m_e}^2}; high\ energy$$

$$P^{(d)}\approx O(1); eE=100MeV/meter, p_\nu=1000TeV$$

$Magnitudes\ of\ Probabilities$

$$m_\gamma c^2 = 10^{-9}\mathrm{eV}^2$$

$In\ magnetic\ or\ electic\ field$

$$P_B = 6.4 \times 10^{-27}(\frac{B}{B_0})^2(\frac{p_\nu}{{p_\nu}^{(0)}})^3; B_0 = 1\mathrm{T}, {p_\nu}^{(0)} = 10\mathrm{MeV}$$

$$P_E = 2.8 \times 10^{-20}(\frac{E}{E_0})^2(\frac{p_\nu}{{p_\nu}^{(0)}})^3; E_0 = 10^3\mathrm{G}V/m, {p_\nu}^{(0)} = 10\mathrm{MeV}$$

l_ν $: mean\ free\ path\ of\ \nu$

Sun

$$l_\nu = 5 \times 10^{15}(\frac{p_\nu^0}{p_\nu})^2\mathrm{m}; m_\gamma c = 1\mathrm{eV}, n_A = 10^{29}/(\mathrm{c}m)^3; p_\nu^0 = 10\mathrm{MeV}$$

$SuperNovae$

$$l_\nu = 6 \times 10^4\mathrm{meters}; \frac{p_\gamma}{m_\gamma c} = 10^7, n_A = 10^{25}/(\mathrm{c}m)^3;$$

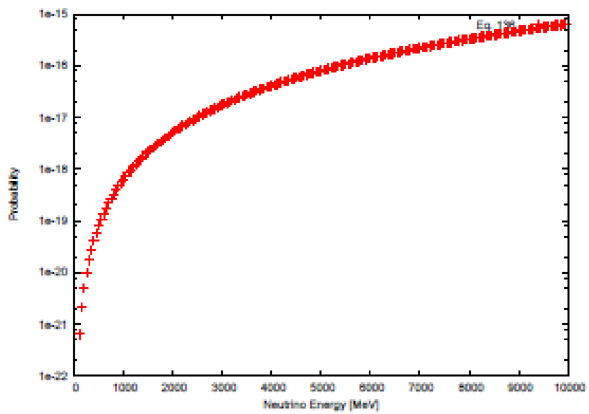


Figure 2: E_ν dependence of the probability Eq. (136) is shown. $B = 10$ Tesla is used for the calculation.

$$P_{\nu+B}(E_\nu); B = 10\text{T}$$

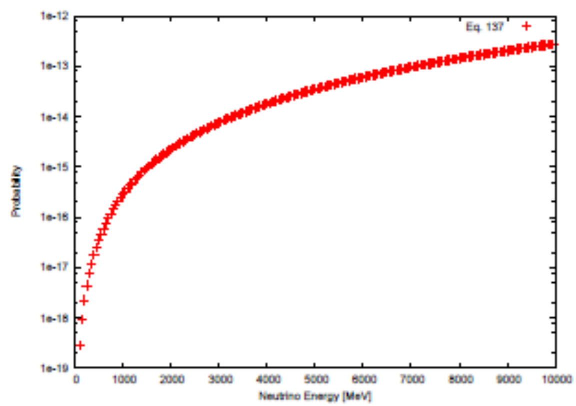


Figure 3: E_ν dependence of the probability Eq. (137) is shown. $E = 100$ GVolt/m is used for the calculation.

$$P_{\nu+E}(E_\nu); E = 100\text{GV/m}$$

$Implications\ of\ \nu + \gamma$

$1.\ high\ energy\ neutrino + "laser"$

$$N_{event} > 10^{-15} \times 10^{20} = 10^5$$

$2.\ neutrino +\ magnetic\ field$

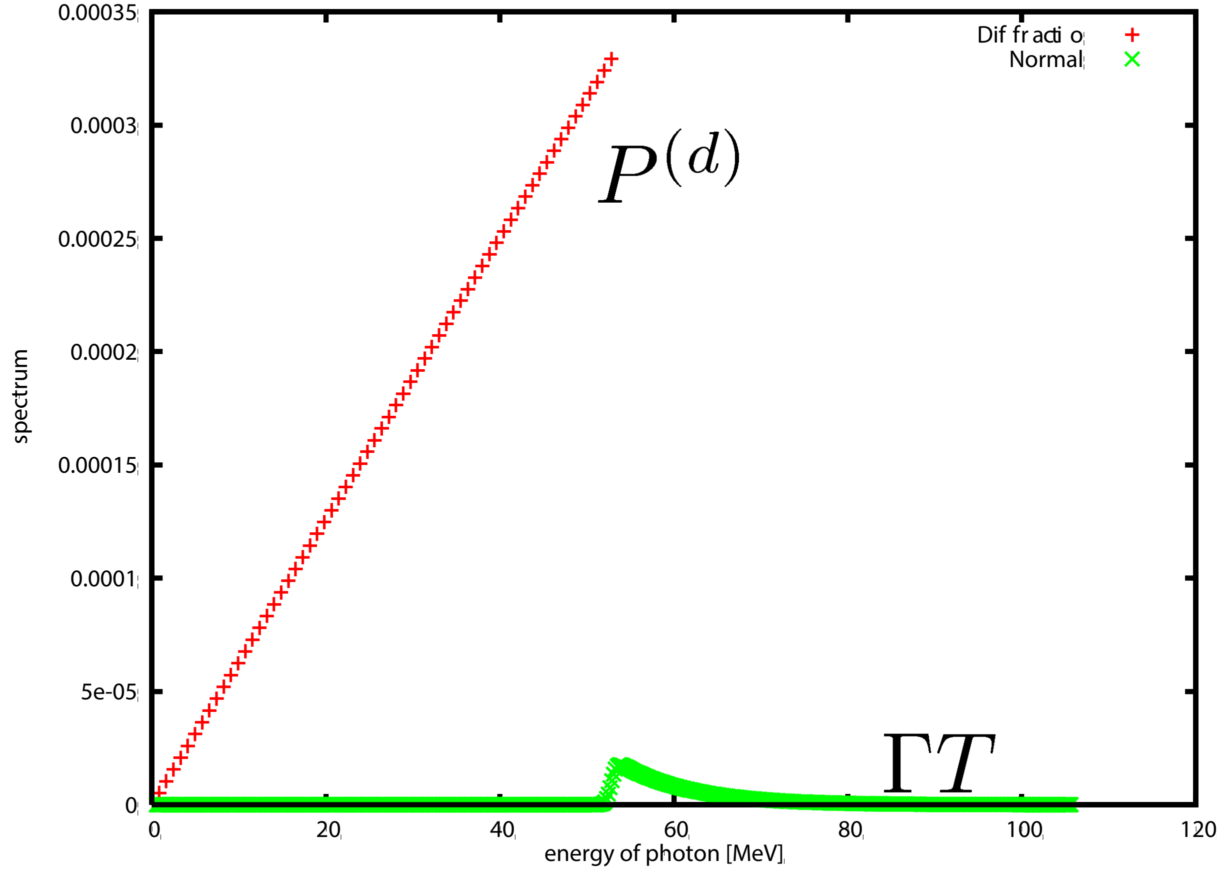
$3\ neutrino + electric\ field\ (Lightning, --)$

$4\ neutrino + photons\ (Sun, SuperNovae,)$

$5\ Relic\ neutrino\ detection$

$5. Di-pole\ transition, nucleus\ transition, QED\ processes$

$$\mu \to e + \gamma, \frac{P^{(d)}(E)}{T\Gamma_0},\ vs\ E_\gamma$$



$$T = 1.7 \times 10^{-8}\mathrm{sec}, m_\gamma c^2 = 1\mathrm{eV}, \sigma_\gamma m_\pi^2 = 100$$

E_γ

$Examples\ of\ P^{(d)}$

(1). $Positron\ \ annihilation$

(2). $Nuclear\ \ reactions$

(3). $Chemical\ \ reactions$

(4). $Others$

(1) $e^+\ annihilation$

$carbon\ hydride(chemical\ reaction)$

Experiment: Enhancement for e^+ annihilation ;Z_{eff}/Z_c

$Ethane$	C_2H_6	37
$Propane$	C_3H_8	135
$Hexane$	C_6H_{14}	2400
$Octane$	C_8H_{18}	8800
$Dodecane$	$C_{12}H_{26}$	18000

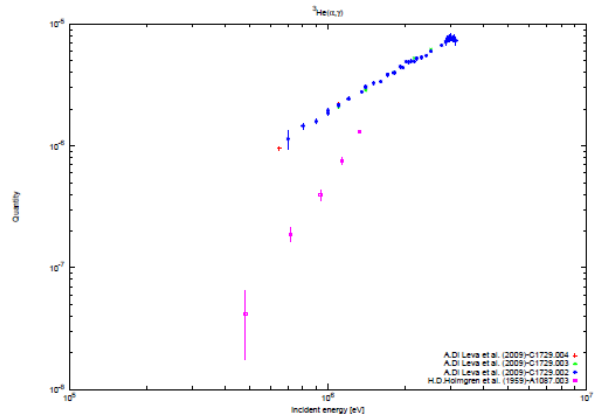
Ref.G.F.Gribakin,et.al,Rev.Mod.Physics,82,2557(2010)

Anomaly in e+ annihilation

$$P^{(d)}/\Gamma_0 T$$

(2) *Nuclear reactions*

$He^3 + He^4 \rightarrow Be^7 + \gamma$(*primodial nucleosynthesis*)



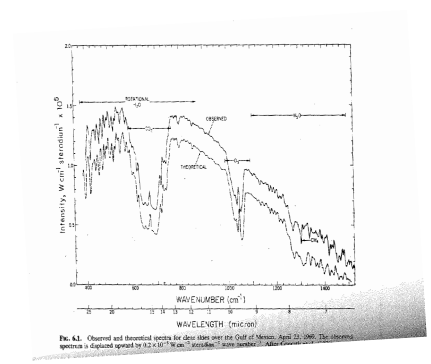
(*HU Nuclear data – center*)

(3) *Absorption Coefficients of Ozone*

Table

Ozone absorption coefficients(cm^{-1})

Wave length	*Inn*	*Hearn*	*Demore*	*Criggs*
2536.5	133.1	133.9	135.0	131.8
2893.6	17.1	17.2	17.3	17.3
2967.3	6.72	6.97	6.85	7.00
3341.5	0.067	0.0498	–	0.065
year	1953	1961	1964	1968



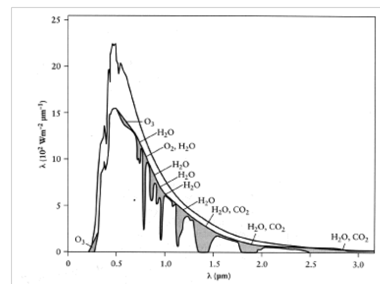


FIGURE 3-4 Spectral distribution of solar irradiation at the top of the atmosphere and at sea level for average atmospheric conditions for the sun at zenith. Shaded areas represent absorption by various atmospheric gases. Unshaded area between the two curves represents the portion of the solar energy backscattered by the air, water vapor, dust, and aerosols and reflected by clouds. Redrawn from J. P. Peinuto and A. H. Oort, *Physics of Climate*. American Institute of Physics, New York. Copyright © 1992 by Springer-Verlag GmbH & Co. Used by permission of the publisher.

Is $P^{(d)}$ *necessary?*

$6.Summary - 1$

Process	Γ_0	$P^{(d)}$	:useful for
1. $\pi \to e\nu_e$	≈ 0	$\frac{E\sigma}{m_\nu^2}$	"determine m_ν"
2. $\nu + \gamma(B,E) \to \nu + \gamma$	0	$\alpha^2 G_F^2 p^2$	$(super\ novae, --)$

$3.Others \quad : e^- + e^+ \to \gamma\gamma; \gamma + e \to \gamma + e$

$(He^3 + He^4 \to Be^7 + \gamma, \ldots), \mu \to e\bar{\nu}_e\nu_\mu, - - - - -$

$Q\bar{Q} \qquad transitions(B^- \to J/\Psi + K^-)$

$Summary - 2$

$1.P^{(d)}\ important\ in\ small\ m, high\ E, small\ T, large\ \sigma$

$2.A' \to A + \gamma;\text{"}negligible\text{"}\ for\ atoms$

$3.\Gamma_0 = 0, P = P^{(d)}$

$4.P^{(d)}\ gives\ macroscopic\ quantum\ effects$