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Lecture IV

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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NEUTRINO PHYSICS

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Q: Can FCNC couplings of massless ν's replace mass-mixing & osc. ?

A: Sometimes.

Literature :
- Wolfenstein 1978
- Guzzo, Masiero, Petcov 1990
- Roulet 1990
- Barger et al. 1991
- Bahcall & Krastev 1997

FCNC of ν's.

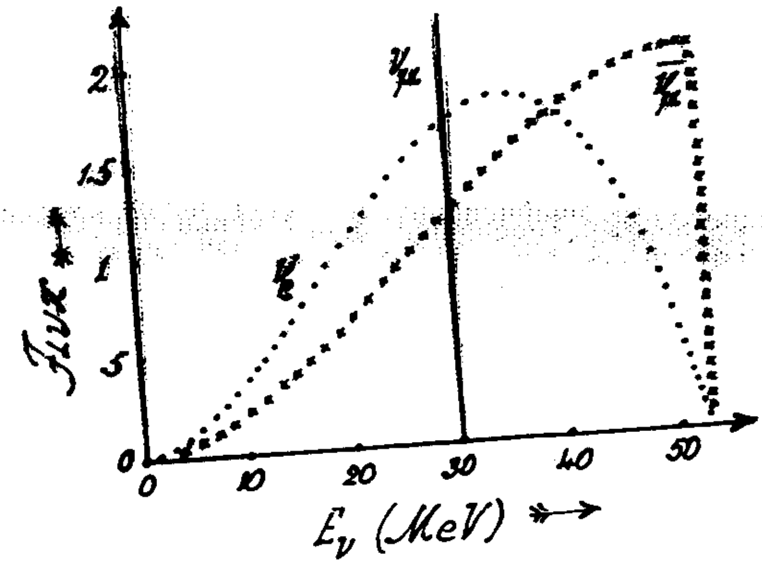
$$\bar{\nu}_{e_L} \gamma_\mu \nu_{\mu_L} \left\{ C^u_L \, \bar{u}_L \gamma_\mu u_L + C^u_R \, \bar{u}_R \gamma_\mu u_R + u \to d + u \to e \right\}$$

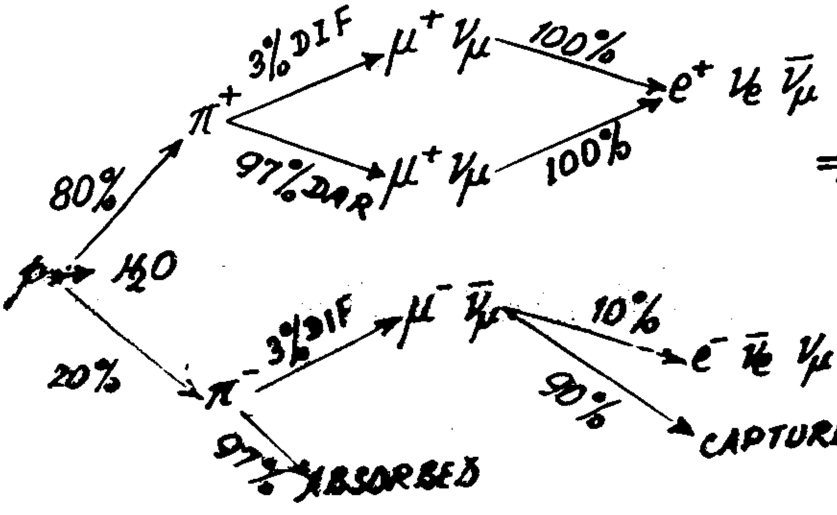
- This has no effect on ν-prop. in vacuum
- In matter there is MSW effect, due to coh. for. sc
- Matter e. states $\neq \nu_e, \nu_\mu$. even if ν's massless.
- Apply to solar ν's
- Find ranges of parameters $C^i_{L,R}$ to explain data.
- Such couplings arise in some SUSY models

$\pi, \mu \to \nu$'s at rest

- $p\,(800\ MeV) \to \pi^+ \to \mu^+ + \nu_\mu$ at rest $\tau_\pi = 26\,ns$

  $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ $\tau_\mu = 2.2\,\mu s$





$\Rightarrow \pi^-$ DIF $\bar{\nu}_e$
is $\sim 6 \times 10^{-4}$
$\sim$ BACKGROUD
TO $\bar{\nu}_\mu \to \bar{\nu}_e$

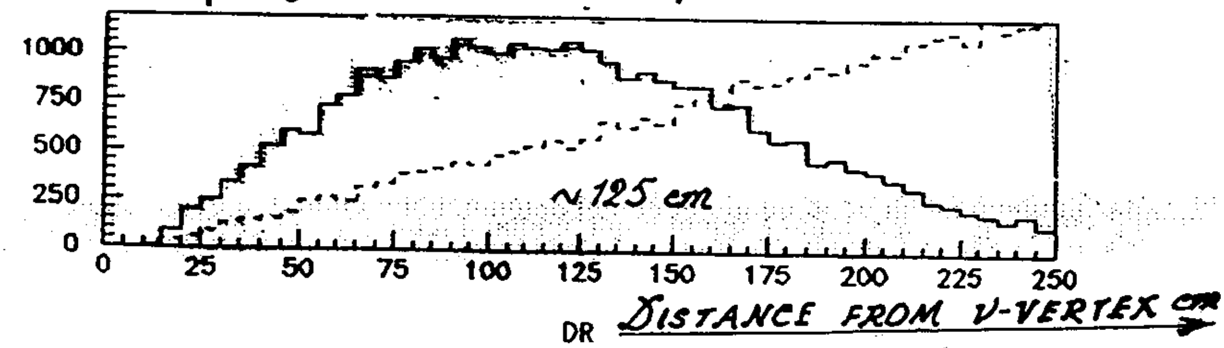
$\bar{\nu}_e$ Detection at L.S.N.D.

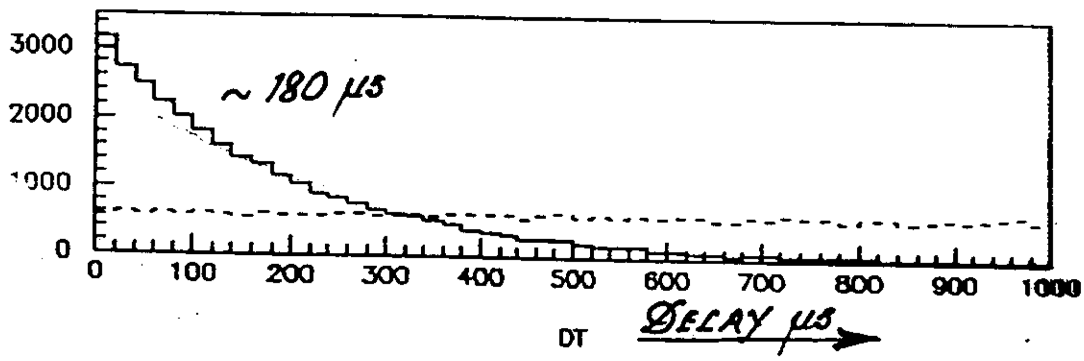
$\bar{\nu}_e + p \to e^+ + n \xrightarrow[t\sim 186\mu s]{} n + p \to d + \gamma$

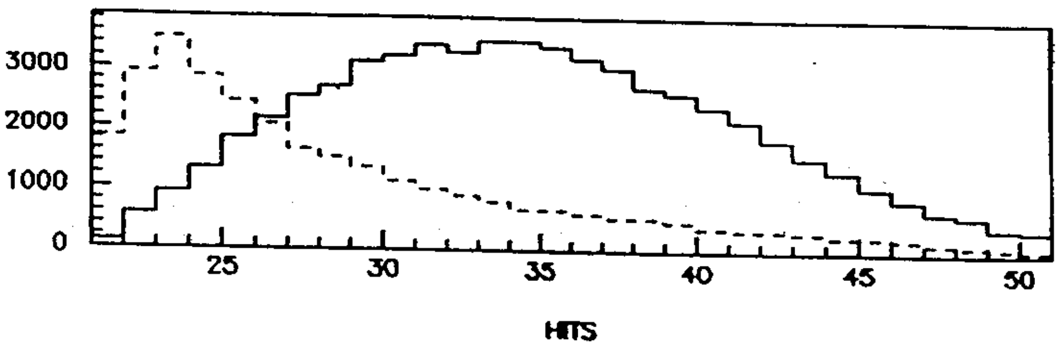
2.2 MeV delayed γ

e-identification
(53 MeV endpoint)

→ signal 2.2 MeV γ ; ⇒ accidental γ

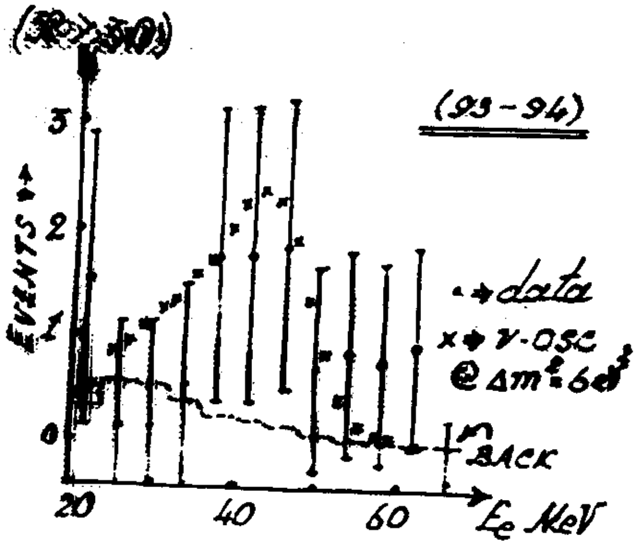






LSND Measurements

- 9 events -vs- 2.12 ± 0.34 in $36 < E_e < 60$ MeV
  ⇒ stat. fluctuation $< 10^{-3}$



Questions

(i) Fid. volume : up - bottom

(ii) $E_e > 60$: in-flight

(iii) Alternative analysis : fiducial cuts?

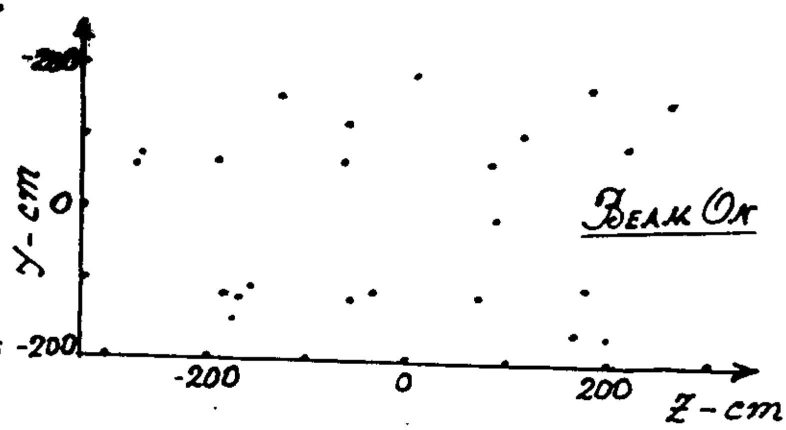
- (93-95) Data:

  ∃ 60% of impro-vement

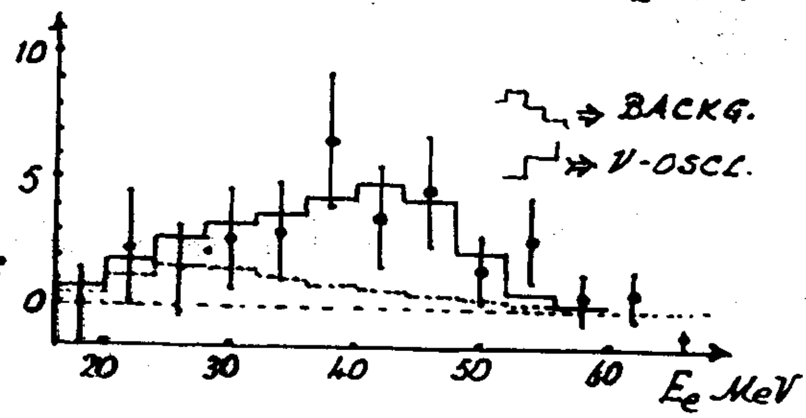
5-60 MeV $\boxed{\text{∃ 22 events -vs- } 4.65 \pm .57}$

out of 6915 EVTS

⇒ stat. fluc. $< 10^{-7}$

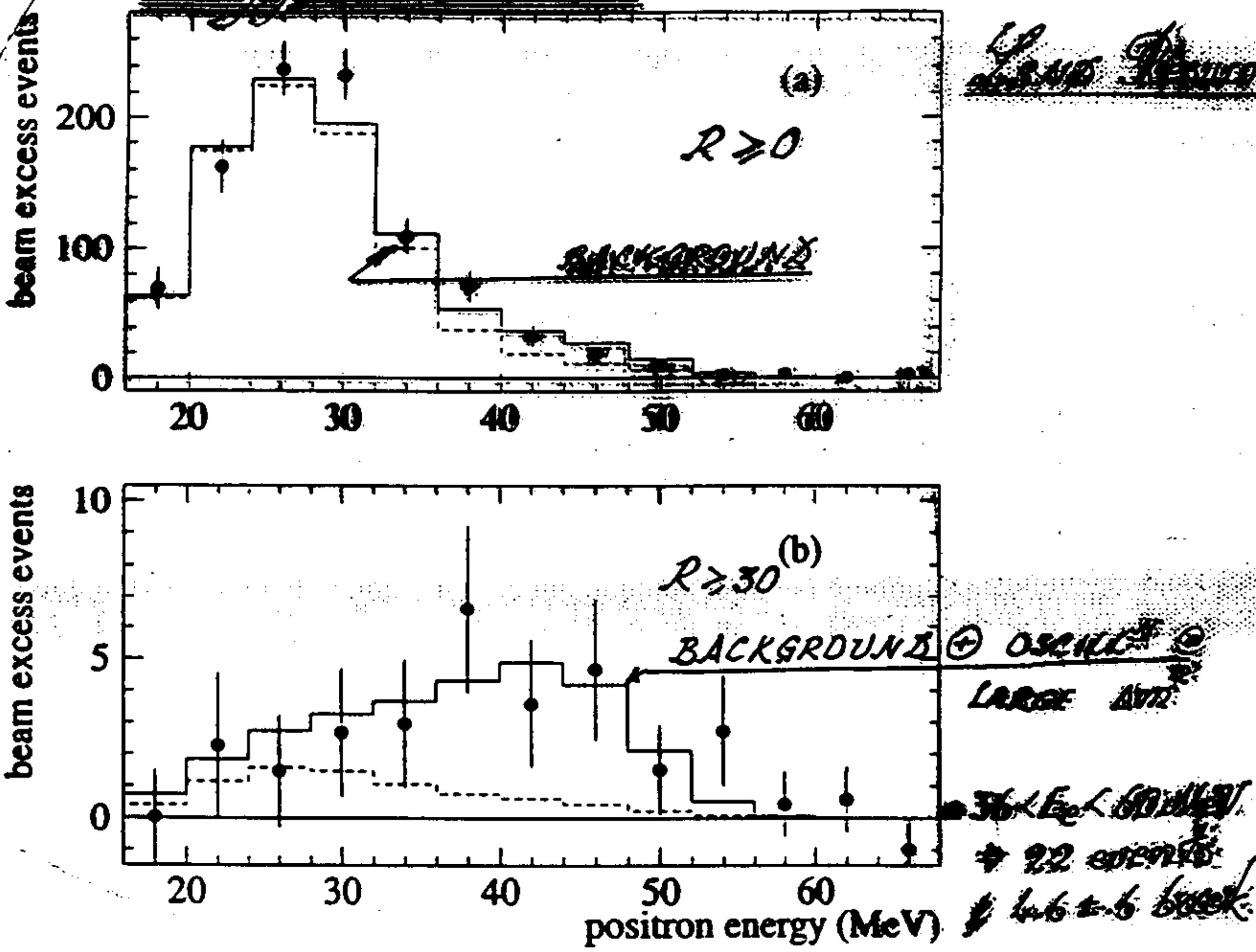


∃ θ_e 'more' consist-ent with oscill. than with isotropic background

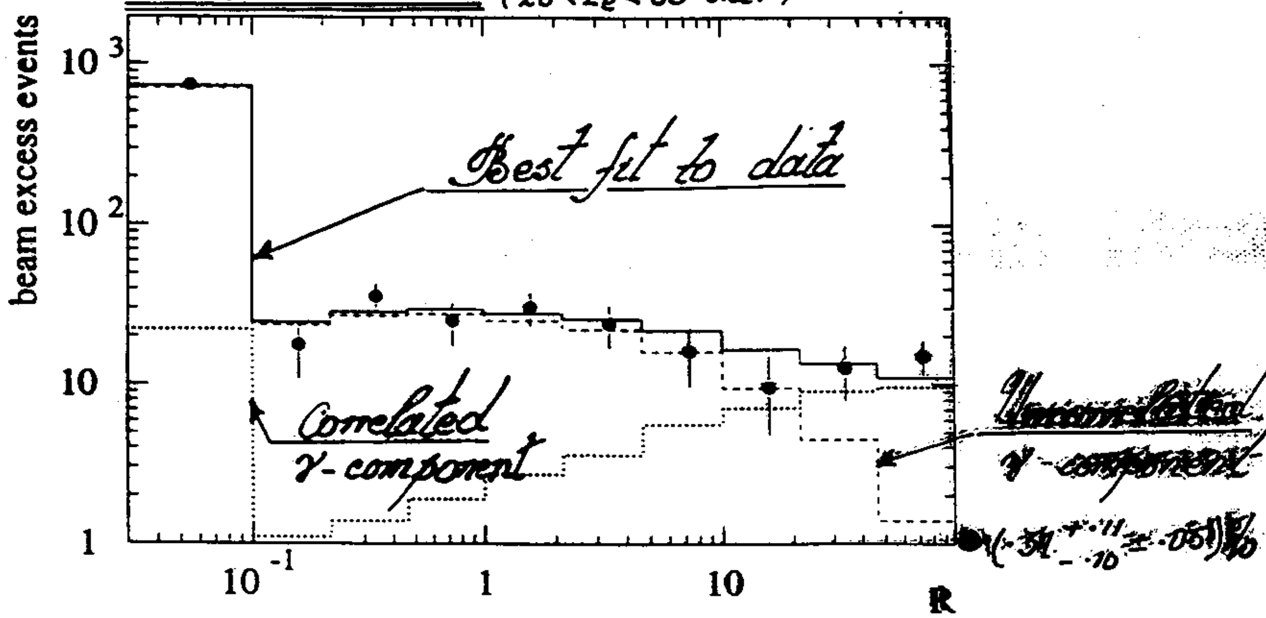


Energy Distribution

LSND Result

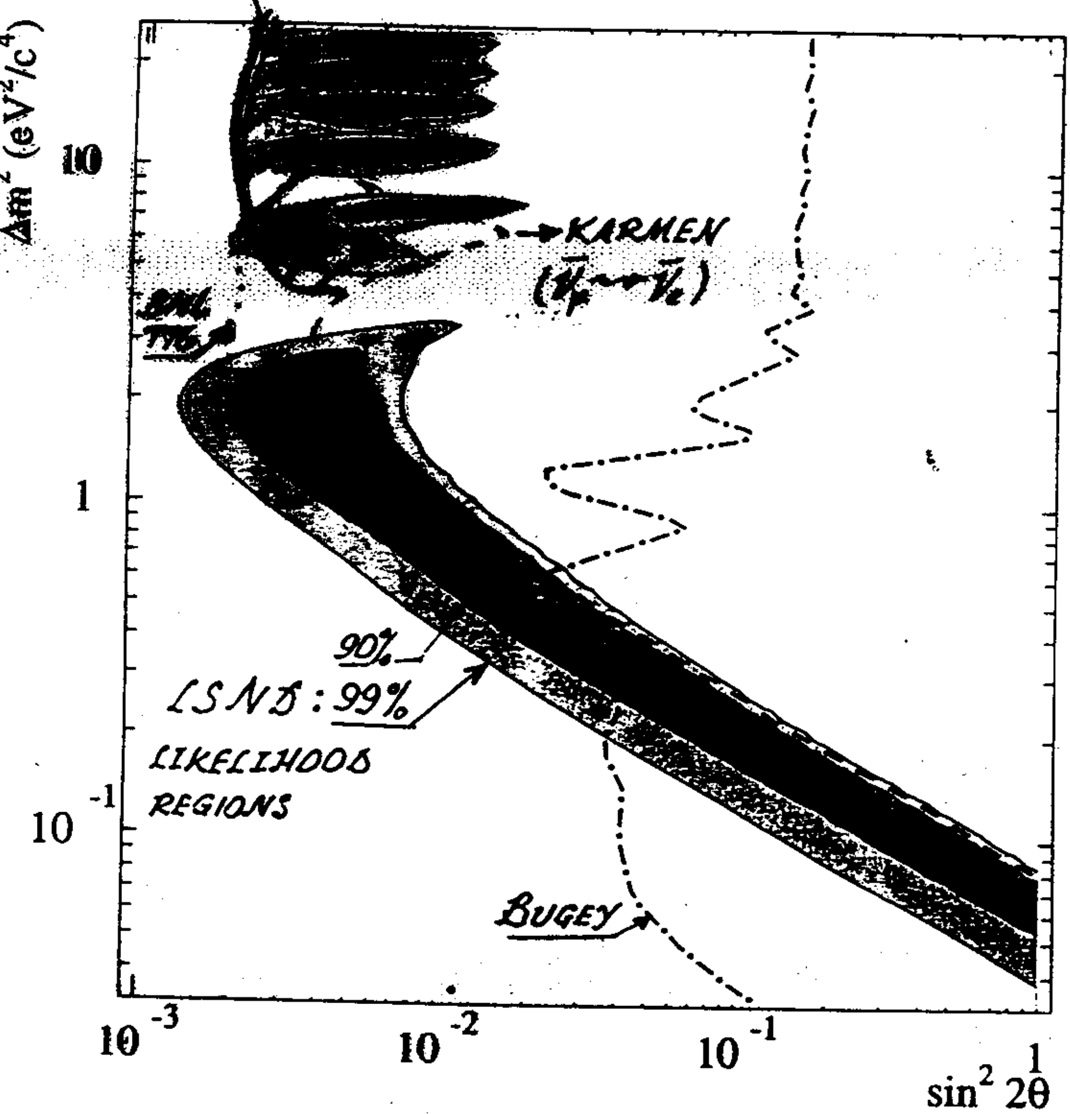


R Distribution ($20 < E_e < 60$ MeV)



new results from (1997) CHORUS/NUMAD rule this out.

$\nu_\mu \rightsquigarrow \nu_e$ OSCILLATION



$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

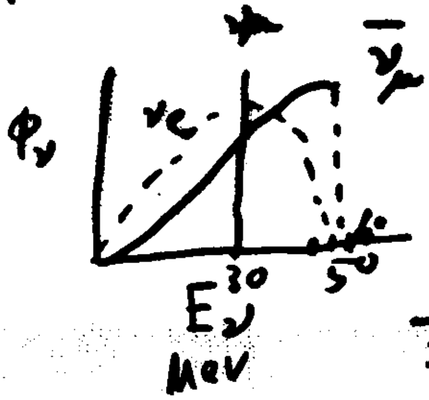
$$\sim 2 \cdot 10^{-3}$$

LSND

$p \to \pi^+ \to \mu^+ + \nu_\mu$ (rest) 26 ns

(800 MeV)

$\quad\quad\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$ 2.2 μs.



$\left[\begin{array}{l} \pi^- \to \bar{\nu}_e \\ \downarrow \\ \mu^- \to e^- \nu_\mu \bar{\nu}_e \end{array}\right.$ $6\cdot 10^{-4}$ BG. $\Big]$

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad E_e \sim 36-60$ MeV

$\bar{\nu}_e + p \to e^+ + n \xrightarrow[186\,\mu s]{} np \to d\gamma$

$\quad\quad e^+ \hookrightarrow$ shower $\quad\quad \gamma \hookrightarrow 2.2$ MeV delayed

22 events, BG ~ 4.65 ev.

Interpret as $\bar{\nu}_\mu \to \bar{\nu}_e$ osc.

Results from decay in flight ~~forthcoming~~ just announced. 6/97

Karmen upgrade (next 2 years)

Forthcoming Reactor $\bar{\nu}_e$ disappearance expts

Palo Verde Experiment
(Former San Onofre Experiment)

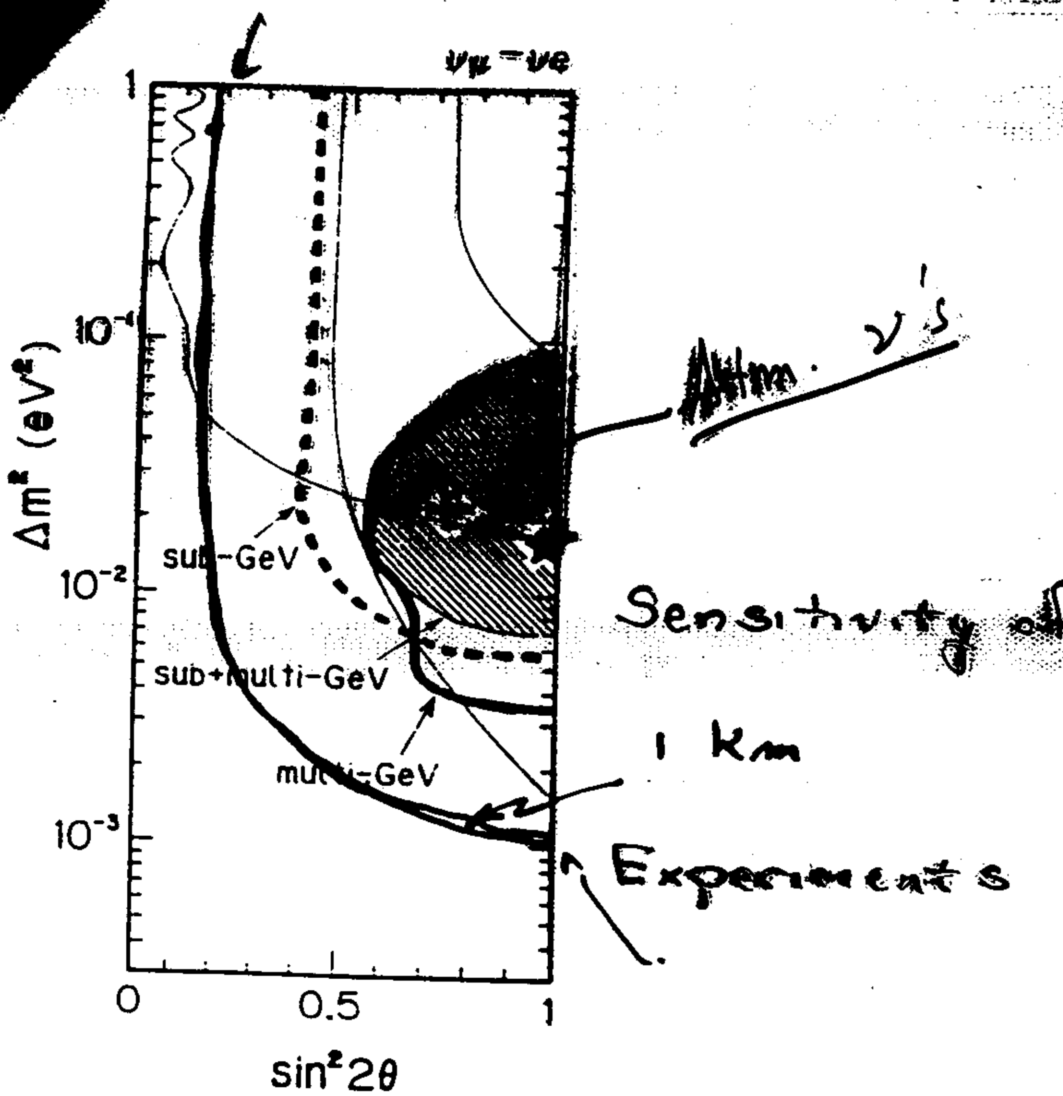
- 12 Ton Gd loaded (0.1%) liquid scintillator.
- 750 m from three reactors – 10,900 MW total thermal power.
- $\bar{\nu}_e$ detection rate of 51 events/day.
- Shallow depth – about 46 mwe.
- Run time: 1 year full power; 2 months 2/3 power (refueling).

CHOOZ Experiment

→ ~~Detector Ready Waiting for Reactors to start operating~~

Now Taking Data

- Target – 5 Ton Gd loaded (0.1%) liquid scintillator.
- Gamma-ray containment – 17 Tons normal liquid scintillator.
- Live shield – 90 Tons normal liquid scintillator.
- 1030 m from two reactors – 8,400 MW total thermal power.
- $\bar{\nu}_e$ detection rate of 31 events/day.
- Deep site – 325 mwe.



Status:

CHOOZ - Detector AND installation complete currently tuning

Palo Verde - Start up April '97

SN1987A (LMC) (Feb 23, 1987)

Expectations for Type II SN:

$M_{progenitor} \gtrsim 10 M_\odot$

implosion $\Rightarrow$ neutronization $e^- p \to n \nu_e$

ρ (10^{11} gm/cm^3 $\longrightarrow$ 10^{14} gm/cm^3)

(only) ν_e's emitted for $\delta t \sim 10^{-3}$ sec.

E (in ν_e's) $\sim$ 1 to 10% of total.

$\sim 0.01\, Mc^2$.

$e^+ e^- \longrightarrow \nu_i \bar{\nu}_i$ (thermal $\nu, \bar{\nu}$'s)

FD distri., $T_{\nu_e} \sim 5$ MeV

$T_{\nu_{\mu/\tau}} \sim 10$ MeV

$N_\nu \sim N_{\bar{\nu}}$

$N_{\nu_{\mu/\tau}} \sim \frac{1}{2} N_{\nu_e}$.

$E_{emitted} \sim E_\nu$, $(E_\nu \gg E_\gamma)$

$\sim \underline{0.1\, Mc^2} \sim (2\text{-}4)\, 10^{53}$ ergs

end-result $\longrightarrow$ conv. wisd. $\to$ neutron star.

$\longrightarrow$ Bethe-Brown (1993) $\longrightarrow \left\{ \begin{array}{l} \text{black hole (often)} \\ \text{nucleon star} \\ (n+p+\bar{K}) \end{array} \right.$

Detection: Water $\hat{c}$ $\begin{cases} \text{Kamiokande} \\ \text{IMB} \end{cases}$

$\bar{\nu}_e p \to n e^+$

$\nu_e O^{16}$ $\qquad \dfrac{\sigma(\bar{\nu} p)}{\sigma(\nu e)} \sim \left(E/\mathrm{MeV}\right)$

$\nu_i e \longrightarrow \nu_i e$

Hence expect $\left. \#(\bar{\nu}_e) \big/ \#(\nu_e) \right|_{\text{observed}} \sim E/\mathrm{MeV}$

Observed Signal:

[IMB + K II] $\sim$ 18 events

$E_{\bar{\nu}_e} \sim 7$ to 30 MeV

$\Delta t \sim 12$ sec

Angular Distri $\sim$? $\begin{cases} \text{perhaps} \\ 1\ \nu_e e \text{ event} \end{cases}$

Deduce: $\left\{ \begin{array}{l} E_\nu^{tot} \sim 3 \cdot 10^{53} \text{ ergs} \\ T_{\nu_e} \sim 4 \pm 1 \text{ MeV} \end{array} \right\}$

Alwarez: "Biggest success of GUTS!"

Constraints on ν Properties from SN1987A

- **$\bar{\nu}_e$ lifetime**: Since $\bar{\nu}_e$'s arrived (more or less intact)

$$\gamma\tau_0 = \tau_{\bar{\nu}_e}(Lab) > R_{LMC}/c \gtrsim 5\cdot 10^{12}\ \text{sec}$$

  - If $\bar{\nu}_e$ not mass e. state, at least the major m.e.s. comp. satisfies
$$\tau_{\nu_i} > 5\cdot 10^{12}\ \text{sec}.$$

From lack of MeV γ rays seen by SMM satellite at SN1987A:

$$\tau_{\nu_e}/BR(\gamma x) \gtrsim 10^{22}\ \text{sec}$$

(for $m_{\nu_i} < 200\,\text{eV}$).

- **ν_e Mass**: Observed Dispersion:

$$\Delta t_{arr} \simeq 12\ \text{sec}.$$

$$\Delta E \sim 10 - 30\ \text{MeV}.$$

$$\Delta t_{ARR} = \frac{R_{LMC}}{c}\,\frac{1}{2}\,(m_\nu c^2)^2\left[\frac{1}{E_2^2} - \frac{1}{E_1^2}\right] + \underbrace{\delta t_{21}}_{\text{dep.}}$$

if δt_{21} neg. or no focussing:

$$m_\nu c^2 \lesssim 20\ \text{eV}.$$

- ν_μ, ν_τ Mass (Dirac).

$$\sigma(\nu_L \to \nu_R) \sim (m_\nu/\mathrm{eV})^2\, 10^{-35}\ \mathrm{cm}^2.$$

If $t_{LR} \sim \frac{1}{\sigma n c} \sim 1/m_\nu^2$ is too small too much energy lost in ν_R escaping.

$$\Rightarrow \quad m_{\nu_\mu/\tau} \lesssim 30\ \mathrm{KeV}.$$

- $\bar{\nu}_e$ electric charge: Intergalactic $\vec{B}$

$\Rightarrow$ deviation from str. line:

$$r = \frac{0.3\,(E/\mathrm{GeV})}{Q_\nu\, B}$$

$$\frac{\Delta s}{s} \sim \frac{1}{24}\, s^2/r^2$$

$\Rightarrow$ Dispersion of $\Delta t \sim \left(\frac{R_{LMC}}{c}\right) \Delta(\Delta s/s)$

Since $\Delta t \approx 12$ sec. $\Rightarrow$

$$Q_\nu < \left(\frac{c\Delta t}{R_{LMC}}\right)\sqrt{24}\left[\frac{\langle E_\nu \rangle}{0.3\, s B}\right]\sqrt{\frac{\langle E_\nu \rangle}{2\Delta E_\nu}}.$$

$$< 10^{-14}\, |e|$$

$\langle E \rangle \sim 1.5 \cdot 10^{-3}$ GeV

$s \sim 1.5 \cdot 10^{21}$ cm

$\frac{\langle E \rangle}{2\Delta E} \sim$ [illegible]

B [illegible]

$R_{LMC} =$ [illegible]

Lab bounds stronger but this is dynamical

- **Neutrino Speed**: Diff. bet. time of ν-signal & first optical sighting: ~ 5 hrs $\sim 2 \cdot 10^4$ sec.

Hence $\Delta t = t_\gamma - t_\nu \gtrsim 2 \cdot 10^4$ sec

$$|1 - v_\nu / c| < \frac{\Delta t}{t} = \frac{2 \cdot 10^4}{5 \cdot 10^{12}} \sim \underline{\underline{4 \cdot 10^{-9}}}.$$

& $V_\nu \sim c$ to a part per billion

- **N_ν = # of Neutrino Flavors.**

If $N_\nu > 3$, luminosity (& flux) in $\bar{\nu}_e$ decreased by $3/N_\nu$.

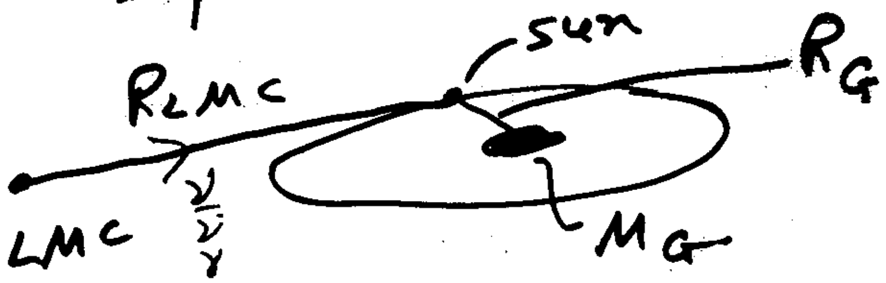
Allowing an uncertainty of factor 2

$$\underline{N_\nu < 6}.$$

LEP (1989) $N_\nu = 3$

Nucleosynthesis $N_\nu < 3.5$

- **Equivalence Principle for $\bar{\nu}_e$'s**



- Gravitational Time Delay Δt_G

$$\Delta t_G = \left(\frac{GM_G}{c^3}\right)(1+\delta_\nu)\,\ln\left(\frac{2R_{LMC}}{R_G}\right)$$

where $\frac{GM_G}{c^3} \sim 3\cdot 10^5$ sec (for $M_G \sim 6\cdot 10^{11} M_\odot$)

$2R_{LMC}/R_G \sim (100\ kpc)/(10\ kpc) \sim O(100)$.

$\rightarrow (\delta t_\nu - \delta t_\gamma) \sim (\delta_{\bar{\nu}} - \delta_\gamma)\cdot 7\cdot 10^7$ sec.

But $\delta t_\nu - \delta t_\gamma < 2\cdot 10^4$ sec

& $\delta_\gamma \sim 1$ (to 1 part in 1000 from Radar Ti...)

Hence $\delta_{\bar{\nu}} = \delta_\gamma = 1$ to one part in 10^3

- **Equivalence Principle for $\nu - \bar{\nu}$**

If one event in ν_e, then since $\delta t_\nu - \delta t_{\bar{\nu}} \lessapprox O(10)$ sec. find

$\delta_\nu = \delta_{\bar{\nu}}$ (to one part in 10^6)

• "Fifth force" coupling ν's to matter
(Long Range).

$$U = -\left[\frac{2GE_\nu M_G}{r} + \frac{q_\nu q_G}{r} + \frac{m_\nu S_\nu S_G}{r}\right]$$

Tensor — vector — scalar

e.g. a vector field $\Rightarrow$ $\delta t_\nu - \delta t_{\bar\nu}$

$$= \left(\frac{m_\nu}{E_\nu}\right)^2\left(\frac{2 q_\nu Q_G}{E_\nu}\right)\left[-\frac{R}{4}/[R_{LMC}^2 + R_G]^2 + \ln\left\{\frac{R_L+\sqrt{R_L^2+R_G^2}}{R_L}\right\}\right]$$

& we know this is $\lesssim O(1-10\,\text{sec})$

From this for dim-less $f_V = q\sqrt{G}$

$$\left.\begin{aligned} f_V^2 &< 2\cdot 10^{-35} \\ f_S^2 &< 10^{-24}\end{aligned}\right\} \text{ for } \underline{m_\nu \sim 10\,eV}.$$

Similarly (for f_S)

• "Secret" $\nu - \nu$ Interactions — $\nu\nu\nu\nu$ or $g\nu\nu M$

• $\nu_{SN} + \nu_{3^\circ K} \longrightarrow$ affect signal.

$\longrightarrow$ $\underline{g < 10^{-3}}$.

Neutrino Properties from SN 1987A.

Signal: 20 events in 15 sec.
$E_\nu \sim$ 10 to 30 MeV.

L: $5\cdot 10^{12}$ L-sec. $4\cdot 10^{53}$ erg. etc.

Assume: $T_\nu \sim 5$ MeV, $E_{tot} \sim 4\cdot 10^{53}$ erg.

<u>Results</u>:

- $\tau_{\bar\nu_e} > 5\cdot 10^{12}$ sec. ($\bar\nu_e$ mass e.state).
- $\tau_{\nu\to\gamma}/BR > 10^{22}$ sec. (Non-obs of MeV γ-ray)
- $m_{\nu_e} < 20$ eV. (Dispersion).
- $m_{\nu_\mu}, m_{\nu_\tau}$ (Dirac) < 30 keV.
- $Q_{\nu_e} < 10^{-14}|e|$. (Dispersion)
- $V_\nu/c < 5\cdot 10^{-9}$ $|t_\nu - t_\gamma|$
- $N_\nu < 6$
- $\delta_\nu = \delta_\gamma$ (to 10^{-3}) $|t_\nu - t_\gamma|$
- $g_{\nu\nu I} < 10^{-3}$
- μ_ν (Dirac) $< 10^{-12}\mu_B$.

Imagine a SN in Galaxy with VLD?

Neutrinos & Cosmology

Early Thermal History of Universe in SM (of cosmology)

. As T drops below 10^{12} K, $\mu^+\mu^-$ annihilate but are no longer made and so disappear.

. At $T \sim 1.3 \cdot 10^{11}$ K, $t \sim 1$ sec. ν's decouple

. At $t \sim 4$ sec & $T \lesssim 5 \cdot 10^{9}$ K; $e^+e^- \to \gamma + \gamma$ and ($\gamma + \gamma \to e^+e^-$ does not take place). Hence T_γ goes up compared to T_ν. By How much?

$\ast$ Ingredients
. In free expansion, entropy is constant.
. $e^\pm$, $\nu, \bar{\nu}$ obey Fermi Stat.
. γ's obey Bose stat.
. Relativistic gas has
$p = \frac{1}{3}\rho$.
$\rho \propto T^4$.

$\left\{ \begin{array}{l} \rho = \text{energy density} \\ p = \text{pressure p.u.v.} \end{array} \right\}$

$$S = \frac{4}{3}\rho R^3/T \left\{ = (\rho + p) R^3/T \right\}.$$

If $S = \text{const} \Rightarrow \rho/T \propto \frac{1}{R^3} \Rightarrow \underline{\underline{T \propto \frac{1}{R}}}$

Before $e^+e^- \longrightarrow \gamma\gamma$ $(T > 5 \cdot 10^9 K)$

$$\rho_{e^\pm, \nu_i, \bar{\nu}_i} = \frac{8\pi h}{c^3} \int_0^\infty \frac{f^3 df}{e^{hf/k_B T} + 1} = \frac{7}{16} a T^4$$

(for each species, ~~[illegible]~~ e, ν_e, ν_μ ~~[illegible]~~)

$$\rho_\gamma = \frac{8\pi h}{c^3} \int \frac{f^3 df}{e^{hf/k_B T} - 1} = a T^4$$

So $S_>$ (entropy p.u.vol. before e^+e^- ann. ~~[illegible]~~ ann.)

is
$$S_> = \frac{4}{3} \frac{R^3}{T} \left\{ \rho_\gamma + \rho_{e^-_L} + \rho_{e^-_R} + \cdots \right\}$$
$$\left(\frac{7}{16} + \frac{7}{16} \cdots \right) = \frac{7}{16} \times 4$$

$$= \frac{4}{3} R^3/T \; a T^4 \left[1 + \frac{7}{4} \right]$$

$$S_> = \frac{11}{3} a (RT)^3.$$

After annihilation only photons:

$$S_< = \frac{4}{3} \frac{R^3}{T} a T^4 = \frac{4}{3} a (RT)^3.$$

But since S is constant.

$$S_> = S_<$$

$$\Rightarrow \frac{(RT)_{T<10^9 K}}{(RT)_{T>10^9 K}} = \left(\frac{11}{4}\right)^{\frac{1}{3}}.$$

& $T > 10^9 K$ is T_ν.

$T < 10^9 K$ is T_γ

Hence $T_\nu(\text{today}) = \left(\frac{4}{11}\right)^{\frac{1}{3}} \underbrace{T_\gamma(\text{today})}_{2.7^\circ K}$

$$\underline{\underline{T_\nu \sim 1.9 \; K}}$$

Number Density: Using F.D. distribution

$m_i = 0$, $\mu_i = 0$:

$$N_{\nu_i} = N_{\bar{\nu}_i} = \int_0^\infty \frac{d^3p}{h^3} \cdot \frac{1}{(\exp(P/T) + 1)} \quad (T = 1.9\; K)$$

$\cong 50$ per cc for each flavor

$N_\nu(\text{tot}) \approx 300$ per cc.

$$\langle p \rangle = \int_0^\infty \frac{d^3p}{h^3} \frac{p}{\exp(p/T)+1} \approx 3.2\, T_p \text{ (decoupling temp)}$$

$$\approx \underline{5.2 \cdot 10^{-4}\ eV/c}$$

Neutrino Flux:

If $m_{\nu_i} \approx 0$, $\quad j_0 = j_\nu + j_{\bar\nu}$

$$\sim N_{tot}\, c$$

$$\sim 10^{13}\ cm^{-2} sec^{-1}.$$

If $m_{\nu_i} \neq 0$ $\quad j \sim \frac{\langle v \rangle}{c} j_0$

$$\sim \frac{\langle p \rangle}{m_\nu} j_0$$

$$\ll j_0$$

<u>could be</u>

For $m_\nu \sim O(10)\,eV$.

$\underline{\langle p \rangle / m_\nu \sim 10^{-4} - 10^{-5}}$

Bound on Total Mass of Neutrinos

Total energy density in ν's is

$$\rho_\nu = 150 \times \sum_i m_{\nu_i} \quad \text{per cc.}$$

Now critical density ρ_c (this corresponds to $\Omega \approx 1$)

is seen to be:

Simple argument due to Weinberg (1st 3 min).

Consider energy of a galaxy

at R:

$$E = \frac{1}{2} m v^2 - \frac{GMm}{R}$$

But $v = HR$, $M = \frac{4\pi}{3}\rho R^3$

So $$E = \frac{1}{2} m R^2 \left[H^2 - \frac{8\pi}{3}\rho G \right]$$

Critical when $E \to 0$, (NR still ok?)

Hence $$\rho_c = \frac{3}{8\pi}\frac{H^2}{G} \approx 10^4 \cdot h^2 \ \text{eV/cc}$$

[$h = \frac{1}{2}$ to 1 fudge factor]

and $\rho_\nu < \rho_c \Rightarrow$ Bound on m_ν.

Hence, since we think $\Omega \leq 1$
(to within factor 2).

$$\sum_i m_{\nu_i} \lesssim 100\, eV. \; (\Omega/\Omega_c)$$

This is the famous Cowsik-McClelland
Gerstein-Zeldovich
Bound.

Actually RHS very uncertain.

- One argument with $H \longleftrightarrow$ age of universe
  & $h_0 > 0.5$, $t_0 < 10\,Gyr$
  $\Rightarrow \Omega \leq 3.$
- Ω can be even larger if $\Lambda \neq 0$
- Many observations suggest
  $\Omega \sim 0.1 - 0.3.$
  but some give $\Omega \sim 0.5 - 1.$
- No real evidence that $\left.\begin{matrix}\Omega = 1 \\ \& \; \rho = \rho_c\end{matrix}\right\}.$

But lots
of prejudice.

ν_τ as Hot Dark Matter Component

If $m_{\nu_\tau} \sim$ ~~7 to 30~~ 1 to 5 eV (95), it could provide 30 to 100 % of a $\Omega \sim O(1)$. This "mixed dark matter" scenario is "fashionable" these days.

Possible Experimental Test

If $m_{\nu_\tau} \gtrsim$ 1 eV &

$m_{\nu_\tau} >> m_{\nu_\mu} \Rightarrow \delta m^2 \gtrsim$ 1 to 1000 eV^2.

$\sin^2 2\theta \sim$ unknown

CERN Experiments in Near Future (approved & funded) $\left[\begin{array}{c}\text{CHORUS}\\ \text{NOMAD}\end{array}\right]$

$$\nu_\mu \longrightarrow \nu_\tau \longrightarrow \nu_\tau + N \longrightarrow \underline{\underline{\tau}}.$$

Detect τ.

will probe δm^2 upto 1000 $eV^2 \rightarrow 1 eV^2$

& $\sin^2 2\theta$ upto 10^{-3}

FNAL Near Detector for LBL
COSMOS $\longrightarrow \sin^2 2\theta \longrightarrow 10^{-4}$.

Back to MBB ν's

Two Possibilities

- $N_{\nu_i} = N_{\bar\nu_i}$, μ_i (chem. pot. $=0$)

- $N_{\nu_i} \neq N_{\bar\nu_i}$ $(\mu_i \neq 0)$

Then $N_\nu - N_{\bar\nu} = \frac{T_\nu^3}{6}\left\{\xi_i + \frac{1}{\pi^2}\xi_i^3\right\}$

$\xi_i \rightarrow \mu_i/T$

For ξ_i large, (degeneracy)

$$N_{\nu_i} \cong \mu_i^3/6\pi^2 \,, \quad N_{\bar\nu_i} = 0$$

$$\langle p_i \rangle \cong 3/4\,\mu_i \qquad (e.g.)$$

Neutrino Refractive Index in Matter

For weak scattering : $(n-1 \ll 1)$

$$n = 1 + 2\pi N_A \lambda^2 (f(0))$$

$f(0) \rightarrow$ forward scatt. ampl.

$N_A \rightarrow$ # atoms / vol.

$\lambda \rightarrow$ ν wavelength.

With SM $\nu f \rightarrow \nu f$ eff. Ham. is

$$H_{eff} = -\frac{G_F}{2\sqrt{2}}\,\bar\nu\gamma_\mu(1+\gamma_5)\nu\left\{\bar f\left\{C_L(1+\gamma_5) + C_R(1-\gamma_5)\right\}f\right\}.$$

C_L & C_R given by SM

$$f(0) = -\frac{1}{2\pi} m_\nu \sum_j \int d^3x \langle p | H_j | p \rangle$$

For material of atom of charge Z, atomic # A; Z protons $(2u+d)$, $A-Z$ neutrons $(2d+u)$

electrons $= Z$

u's $= (A+Z)$

d's $= (2A-Z)$

For ν_e's. $$f_{\nu_e}(0) = -\frac{G_F E_\nu}{2\sqrt{2}\pi}(3Z-A)$$

ν_μ, ν_τ. $$f_{\nu_\alpha}(0) = 4\frac{G_F E_\nu}{2\sqrt{2}\pi}(A-Z)$$

$$f_{\bar\nu}(0) = -f_\nu(0).$$

$$n = 1 \pm \frac{G_F N_A (3Z-A)}{\sqrt{2} E_\nu} \quad \nu_e(\bar\nu_e)$$

$$n = 1 \mp \frac{G_F N_A (A-Z)}{\sqrt{2} E_\nu} \quad \nu_\alpha(\bar\nu_\alpha).$$

Detection of Relic ν's

Many Proposals : · Surface effects (G_F) $\times$
(reflection / refraction)

$[\nu \not\equiv \bar{\nu}]$ · e spin rotation $\checkmark$
SC, quench $\underline{B}$?

$\frac{d\phi_\nu}{dE}$  · $\nu\bar{\nu}$ on Z-resonance ?

$E_R = \frac{m_Z^2}{2m_\nu}$ $\nu_{HE} + \nu_R \longrightarrow Z^0$ $\hookrightarrow$ Dip
$(m_\nu \neq 0)$. $\boxed{G_F^2}$

· Volume Effect
Loosely filled object w. spheres of size $a \sim \lambdabar$ (ν-wavelength). ($d < \lambdabar$). Less than half full.

Typical accn. is :

$$a \sim (N_\nu v)\left(\frac{\sigma_0 N_A K_L^2}{A m_N}\right)(2 m_\nu v)$$

$$K_L = A - Z \} \nu_\mu \qquad = 3Z - A \} \nu_e$$

$$\sim 10^{-22} (K_L/A)^2 \ \mathrm{cm/s^2}$$

Can such objects be made & such small accelerations observed?

Detection of MBB ν's

(1) Surface Effects

* . Reflection

total reflection $\longrightarrow 0$ unless ν flux peaked sharply in direction

. Even if this satisfied, effects due to two surfaces cancel.

. To avoid this propose stack of mirrors.

. Even then penetration depth for low energy ν's $l \gtrsim \frac{1}{2\pi} \frac{\lambda}{\sqrt{n-1}}$ is quite large $\sim 20m$

hence almost no reflection.

* . Refraction. momentum transfer

is $\frac{dp}{dt} = \underset{\text{area}}{S}\,(n-1)\underset{\langle p_\nu \rangle}{p}\,(j_\nu - j_{\bar\nu})\,\alpha$ ← geometric factor

$\longrightarrow 0$ if $j_\nu = j_{\bar\nu}$; otherwise

$\alpha \longrightarrow 0$. by Gauss.

Surface Effects No Good!

Spin Rotation (Stodolsky et al.)

Consider a polarised e moving in ν-sea. The net CC + NC interaction is p.v. & can change its polarization.
Consider CC, the electron part:

$$\bar{\psi}_e \gamma_\mu (1+\gamma_5)\psi_e \xrightarrow[v/c \ll 1]{} \chi_e^{+}(1-\underline{\sigma}\cdot\hat{\underline{n}})\chi_e$$

$$\hat{\underline{n}} = \underline{v}/|\underline{v}|$$

- Calculate ΔE due to this interaction $\langle \chi_e^{+}(H = H_{cc} + H_{NC})\chi_e \rangle$

- In ν rest frame, ν-velocities are isotropic, $\rho = \rho_\nu$ & $\underline{v}$ = electron vel.
In electron rest frame ρ_ν gets distorted & ν-current density is

$$\underline{J} = \frac{2\rho\,\underline{v}}{\sqrt{1-|\underline{v}|^2}} \qquad (c=1)$$

The effective curr. int. in this frame (spin-dep. part) is

$$2 \cdot \frac{G_F}{\sqrt{2}} \cdot \underline{\sigma}_{el} \cdot \underline{J}$$

The $\Delta E_{cc} = \dfrac{2\sqrt{2}\, G_F\, \rho\, v}{\sqrt{1-v^2}}$ (due to cc)

(This is assuming $\rho_\nu >> \rho_{\bar{\nu}}$ or complete deg. degeneracy; if not ρ is replaced by $\rho_\nu - \rho_{\bar{\nu}}$).

$$\rho = \frac{1}{6\pi^2} \cdot p_F^2 \qquad p_F = \text{fermi mmtm}$$

For NC interaction only axial current contributes which $\propto T_3^L/2$ $= \frac{1}{2}$ for ν & $-\frac{1}{2}$ $\bar{\nu}$'s. Hence

$$\Delta E_{NC} = \Delta E_{cc}(T_3/2) \quad \text{(for deg.)}$$

Total : $\Delta E = \Delta E_{cc}[1 + T_3/2]$

let $v' = \dfrac{v}{\sqrt{1-v^2}}$

$$\underline{\Delta E = 2\sqrt{2} G_F v' [1 + T_3/2]}$$

→ This will cause change of pol.

It is like light (polarised) passing thru optically active medium.

If initially e is polarized along x, travelling along z; then it picks up some pol. along $-x$. Or the spin rotates around the line of flight (due to P.V.)

In e rest frame the angle of rotation ($\equiv$ phase diff. bet. two helicity comp.) $\phi_e = \Delta E \, t_e$

t_e ↳ time spent in medium

In ν rest frame $t_\nu = \dfrac{t_e}{\sqrt{1-v^2}}$.

$$\phi = 2\sqrt{2}\, G_F \rho \,(v t_e) \underbrace{\left(\frac{1}{\sqrt{}} \times \sqrt{}\right)}_{1}$$

$$\left\{1 + \tfrac{1}{2} T_{3L}\right\}$$

For $p_F \sim eV$

$$\phi \sim 3\cdot 10^{-20} \left(p_F/eV\right)^3 \left(1 + \frac{T_{3L}}{2}\right) \text{ rad/cm}$$

$$\phi_{\nu \text{ massive}} \sim \Phi/2 .$$

<u>Estimates</u>. From $\rho_\nu \lesssim \rho_c$, ~~get~~

~~[illegible]~~ & $v_{\text{Solar Sys}} \sim 300$ km/s

get $\phi \sim 0.1$ sec/yr.

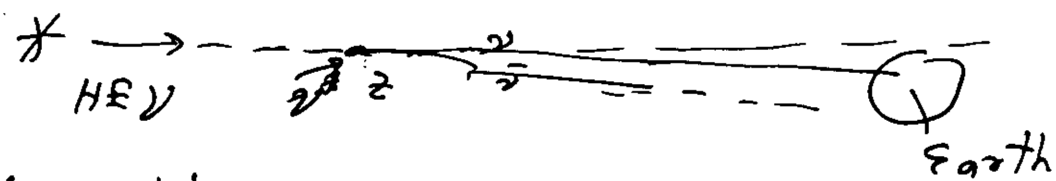
v. small.

- Use Superconductor – Josephson.
- Quench Earth m.f. . etc
- <u>Perhaps Some day in future.</u>

$\nu\bar{\nu}$ Annihilation on the Z (Weiler 1984)

- Let ν's have mass $m_\nu \sim O(eV)$.
- Let there be sources of V.H.E. ν's (AGNs etc.) $E \gtrsim 10^{21}$ GeV.

Then from the source to the earth $\nu_{HE} + \bar{\nu}_{MBB} \longrightarrow Z^0$ is



possible and one should see an absorption "line" in the spectrum at an energy E_Z given by

$$m_\nu + E_Z \simeq \sqrt{m_Z^2 + E_Z^2}$$

$$E_Z \simeq \frac{m_Z^2}{2m_\nu} \sim 4 \cdot 10^{21}\ eV$$

$$\sim 4 \cdot 10^{12}\ GeV. \quad \text{for } m_\nu \sim eV.$$

Including the red-shift for very distant sources.

$$\tilde{E}_Z = \frac{E_Z}{1+z}$$

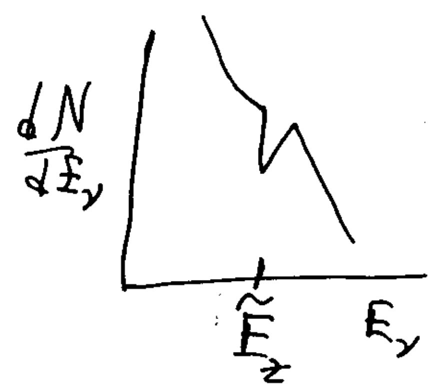
- $\sigma_Z \sim \frac{G_F^2 m_W^2}{\pi} s/m_Z^2 \sim 10^{-33}\ cm^2$

- Need $\Phi_\nu \sim 10^{-13}\ m^{-2}\ sec^{-1}$ for detectability of the absorption dip.

- Then if distance $\sim 10^4$ mparsec then its total energy output/yr is $\sim 10^5\ m_\odot/yr$!

- Perhaps not one but many point sources?

- Unlikely but v. interesting



- Volume Effect (Zeldovich et al.)

  - Need $m_\nu \neq 0$
  - Assume clustering around Galaxies
  - Then ν's moving like solar sys.
  - Motion of earth makes, ~~get~~ ν flux anisotropic
  - ν - matter scattering gives mmtm transfer → force on bulk matter → net acceleration of a macroscopic object → to be measured.

<u>Aside:</u> $\mathcal{L}_{eff}$ for ν scatt. on atom: $N_e = Z$, $N_u = A + Z$

$N_d = 2A - Z$.

$$\mathcal{L}_{eff}: \frac{4G_F}{2\sqrt{2}} \, \bar{\nu}_e \gamma_0 \nu_e \Big[\left(-1 - \tfrac{1}{4}\right) Z + Z x_W + \left(\tfrac{1}{4} - \tfrac{2x_W}{3}\right)(A+Z) + \left(-\tfrac{1}{4} + \tfrac{1}{3} x_W\right)(2A - Z) \Big]$$

- x_W terms cancel.
- goes as $(3Z - A)$.

Similarly ν_μ, ν_τ go as $(A - Z)$.

<u>ν-scattering on a spin-0 Nucleus</u>

$$\frac{G_F}{\sqrt{2}} \bar{\nu}_L \gamma_\mu \nu_L \, (k + k')_\mu .$$

$$\longrightarrow \quad \sigma = \frac{G_F^2 m_\nu^2}{\pi}$$

(for low energies $E_\nu \sim m_\nu$)

Assuming total reflection (best case)

$$\Delta p \simeq 2 m_\nu v_\nu$$

Hence $f = \frac{dp}{dt} = j_\nu \sigma \Delta p$

$(j_\nu = N_\nu v)$

$$\Rightarrow f = N_\nu v \, \sigma_0 N_A^2 k^2 \, 2 m_\nu v$$

$$= 2 N_\nu \cdot \sigma_0 \cdot N_A^2 k^2 m_\nu v^2.$$

- $N_\nu \sim 10^7/cc$ (enhanced by clustering)
- $v \sim 10^7$ cm/s
- $\rho \sim 100$ gm/cc (optimistic)

$$a = \frac{f}{m} = \frac{f}{A N_A m_p} = 10^{-22} (k/A)^2 \text{ cm/sec}^2$$

could be off by several orders of magnitude

Can this ~~[illegible]~~ be measured?

Current sensitivity far a 10 orders of magnitude off!

Proposal: Consider an object made up of small spheres of radii $a \approx \lambdabar$ (ν wavelength) packed loosely (i.e. pores $\lesssim \lambdabar$).
[If more than $\frac{1}{2}$ filled or packed too tight, amplitudes interfere to reduce the effect].

- # atoms in the object N_A

$$N_A = \left(\frac{\rho}{A m_p}\right)\left(\frac{4\pi}{3} r^3\right)$$

r = rad. of pellets

- $$\sigma_\nu = \frac{G_F^2 m_\nu^2}{8\pi} N_A^2 K^2$$
$$= \sigma_0 N_A^2 K^2$$

where $K = (A - Z)$ $\quad \nu_\mu, \nu_\tau$
$= (3A - Z)$ $\quad \nu_e$

Nucleosynthesis & N_ν

- ^4He abundance(=f) is about 24%
- primordial ^4He formed at $T > 100$ keV & all n's involved then

$$f \sim \frac{2\alpha}{1+\alpha} \qquad (\alpha = \#n/\#p)$$

Saha Eq.

- $T^* \sim 0.7$ MeV when $n \longleftrightarrow p$ rate falls & α freezes.
- $\alpha = e^{-\Delta/T^*} \sim 1/7. \Rightarrow f \sim 1/4.$

for $N_\nu = 3$ & fixed $\eta_B = N_B/N_\gamma$.
($\sim$ few $\cdot 10^{-10}$)

If $N_\nu > 3$, T^* & α increase & f increases:

roughly $\delta f \sim \frac{1}{20}\,\delta N_\nu$.

$N_\nu < 3.8$ or something.

Schvartzman

LEP $\Rightarrow$ $N_\nu = 3$