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SMR.858 - 35

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SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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NEUTRINO PHYSICS

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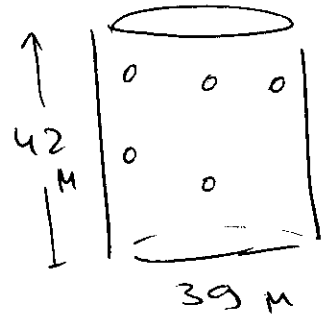
Please note: These are preliminary notes intended for internal distribution only.

NEUTRINO PHYSICS

A. Smirnov

1 In January – February 96, huge steel tank situated in cavity of Kamioka mine will be feeled by water



- 11.200 PMT will look ~~this~~ tank
- 50.000 T. of water

- In April 96 the electronics will turn on and underground detector of new generation will start to operate

SUPERKAMIOKANDE

- Also in '96 Sudbury (Canada) detector with 1000 t of heavy ~~wt~~ water is expected to begin to work.
- There is a hope that these detectors will give the answers to the questions we will discuss in ~~the~~ our lectures

2. After top quark discovery, the neutrinos are the only known fermions with unknown masses.

ν-masses & mixing are main issues of these lectures

$\boxed{m_\nu \\ \theta_\nu}$

Why the knowledge of ν-masses and mixing is so important?

① Important implications to Cosmology and astrophysics:

- $\Omega_\nu \sim O(1)$
- structure formation in the Universe
- Nucleosynthesis
  - primordial
  - in stars
- Stars evolution
- relation to → Baryon asymmetry of the Universe

② knowledge of $\boxed{m_\nu, \theta_\nu}$ may shed some light on

- fermions mass problem
- quark-lepton symmetry
- L- and B- violation

3: Via neutrino masses one can get some information on very large scales:

$$M \sim \frac{v_{ew}^2}{m_\nu}$$

v_{ew} – is the electroweak scale

m_ν – neutrino mass

$M = ?$ 10^{10} GeV

10^{12} –

10^{16} –

10^{18} – ?

M_{pl} – ?

Plan of lectures:

ν – mass mixing

EFFECTS

- oscillations
- Resonance conversion

Bounds & Hints

- solar ν
- atmospheric neutrinos
- HDM
- LSND
- Karmen
- NS.

implications

- Scenarios
- pattern
- mechanisms

NEUTRINO FLAVOURS

ν_e, ν_μ, ν_τ ← states with definite flavours

• <u>phenomenological definition:</u>

ν_e — is the state which interacts with electron: (positron)

$\pi \to e^+ \nu_e$

ν_μ — " — with muon

ν_τ — " — τ - lepton

• <u>In the Standard Model:</u>

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

→ they form the doublets
→ enter the corresponding charge currents.

• In general these two definitions may not coincide:

ν_e state which is produced in β-decay $\neq$ ν_e - state which enter the same doublet with electron

- This situation is realized in quite probable case of existence of heavy neutral leptons (= or heavy "RH" neutrinos)
  - it is realized in the <u>see-saw</u> mechanism

<u>Example:</u>

$$\begin{pmatrix} \overset{\approx 1}{\nu_e'} + \epsilon_e N \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \overset{\approx 1}{\nu_\mu'} + \epsilon_\mu N \\ \mu \end{pmatrix}_L$$

Let $m_N \geq \frac{m_Z}{2}$ (to avoid LEP bound)

$\Rightarrow$ N can not be produced in β-decay or in π decay (for kinematic reasons)

$\Rightarrow$ the state which enter the same doublet with e: is

$$\nu_e = \nu_e' + \epsilon_e N$$

the state which is produced in β-decay is ν_e'

ν_e and ν_μ are orthogonal, but not ν_e', ν_μ':

$$\langle \nu_e | \nu_\mu \rangle = \langle \nu_e' | \nu_\mu' \rangle + \epsilon_e \epsilon_\mu = 0$$

$$\Rightarrow \boxed{\langle \nu_e' | \nu_\mu' \rangle = - \epsilon_e \epsilon_\mu}$$

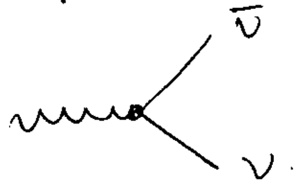
violation of lepton number

The bounds on ϵ: $\underline{\epsilon \lesssim 10^{-2}}$

(breaking of the universality etc)

- Number of neutrino flavours ($\equiv$ species)

Γ_{inv} — invisible width of Z^0 — decay:



$$\Gamma_{inv} = \Gamma_{tot} - \Gamma_{\ell} - \Gamma_{h}$$

leptonic hadronic

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu}$$

LEP: $\boxed{\Gamma_{inv} = 499.5 \pm 2.7 \text{ MeV}}$

Γ_ν is the $Z \to \nu\nu$ width in SM:

$$\boxed{N_\nu = 2{,}987 \pm 0{,}016}$$

→ strong bounds on <u>new physics</u>

e.g. – new neutrino species

– on couplings of new light scalars etc.

one subtle point:

what is the neutrino state produced in Z^0 decay?

If L-number is conserved, then one has independent (incoherent?) production of pairs $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$. However, if lepton numbers are broken these pair can be

L_e, L_μ, L_τ

mixed. May be more natural in this case to consider the production of the mass states:

$$\nu_1\bar{\nu}_1, \nu_2\bar{\nu}_2, \nu_3\bar{\nu}_3.$$

In fact, ~~the~~ as follows from the Lagrangia the state which is produced in Z^0 decay is

$$|\nu_Z\rangle = \frac{1}{\sqrt{3}}\left[|\bar{\nu}_1\rangle|\nu_1\rangle + |\bar{\nu}_2\rangle|\nu_2\rangle + |\bar{\nu}_3\rangle|\nu_3\rangle\right]$$

One can easily check that this state gives the same invisible width of Z^0 as three pairs $\bar{\nu}_i\nu_i$:

$$\Gamma^{inv} \sim |\langle\nu_Z|L|Z^0\rangle|^2 = 3\left(\frac{g}{2}\right)^2$$

According to recent reanalisys of the ~~[illegible]~~ Primordial Nucleosynthesis, the bound on the effective number of neutrino species ~~[illegible]~~ in the time of Nucleosynthesis (~ 1 sec) is

$$\boxed{N_\nu < 2.5 \quad (95\%)\ \text{C.L.}}$$

This could imply that ~~[illegible]~~ some of neutrinos are unstable, e.g. ν_τ, having the mass ~

$$m \sim 10 - 20 \text{ MeV}$$

and the life time:

$$\tau < 10 \text{ sec.}$$

$$\nu_\tau \Rightarrow \Phi + \nu_\mu$$

where Φ is the Majoron-like particle.

NEUTRINO MASSES

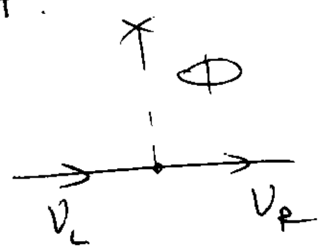
(1). In the Standard Model:

$m_\nu = 0$.

(2). If there are right handed neutrino components ν_R one can introduce Dirac mass term:

$$\mathcal{L}_D = -m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) \qquad (*)$$

it has the weak isospin 1/2 and can be generated by Yukawa couplings with Higgs doublet:



3) In the mass term (*) instead of ν_R one can use $\underline{(\nu_L)^c}$: charge conjugated state ~~etc~~:

$$\mathcal{L}_M = \frac{1}{2} m(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L)$$

$$[(\nu_L)^c = C(\bar{\nu})^T] \qquad C \equiv i\gamma^2\gamma^0$$

This term can be rewritten as:

$$\frac{1}{2} m \left(\bar{\nu}_M \nu_M \right)$$

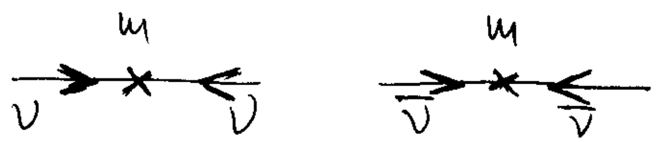
where

$$\nu_M = \nu_L + (\nu_L)^c$$

and ν_M has evident property:

$$(\nu_M)^c = \nu_M .$$

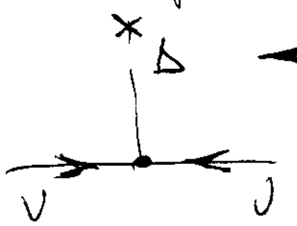
$\Rightarrow$ majorana neutrino



majorana mass terms.

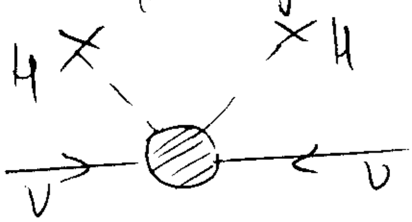
$\Delta L = 2$ – violate lepton number
$I = 1$ weak isospin

How to produce them?

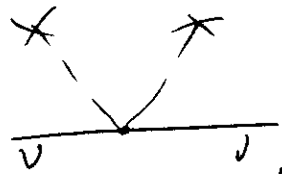


← ~~electroweak~~ triplet of Higgses

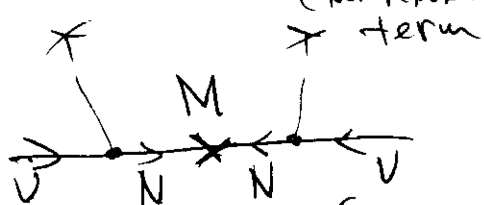
or effectively



: gravity(?)



(NON RENORMALIZABLE term)



(see-saw)

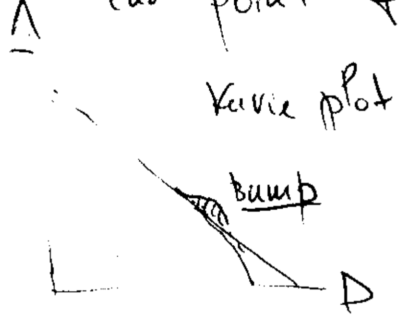
$\boxed{\text{Bounds on } \nu\text{-masses}}$

kinematics. (Best).

Summary:

ν_e: ${}^3H \to He + e^- + \bar{\nu}_e$

end point of the energy spectrum:



INR, RAS: integral electrostatic spectrometer

$m < 4.5\ eV$ 95% cl.

look (ν)

Mainz: 6. eV ?
7.2 eV

(ν_μ): PSI

$\pi \to \mu\, \nu_\mu$

$\to$ $M(\nu_\mu) < 160\ keV$ ( )

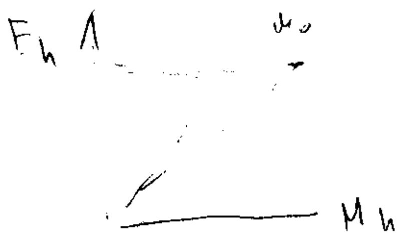
(ν_τ): ALEPH CERN.

152 000 τ-decays.

$\boxed{\tau \to 5\pi(\pi^0)\, \nu_\tau}$

$m_h > 1.62$ G

- Measure: $\left(\frac{E_{had}}{E_{Beam}}\right)$
- M_{had} (GeV)
  τ invariant mass of hadron



$$\boxed{m(\nu_\tau) < 24\ \text{MeV}} \quad (95\%\ \text{cl}).$$

$m_h < m_\tau - m_{\nu_\tau}$ ← our ~~deviation~~ dimension plane

But if there is a mixing? with light neutrinos.

➔ there is some probability that one detect some event

- but the mixture should be very small.

  $\nu_e - \nu_\tau$ (if majorana...)

- ν_s — NS'.
- ν_μ = ?

<u>Cosmological bound:</u>

$$\Omega_\nu \cdot h^2 = \sum_i \frac{m_\nu}{92\ \text{eV}}$$

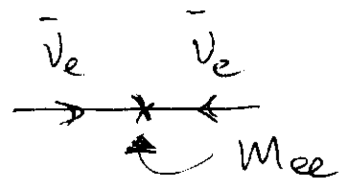
$$t > 1.3 \cdot 10\ \text{yr} \Rightarrow \Omega_0 h^2 < 0.4$$

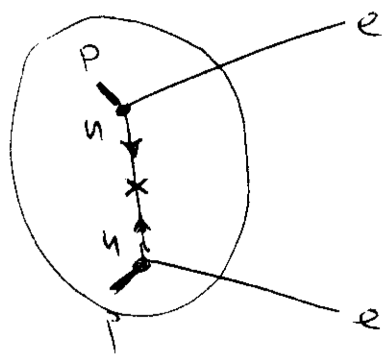
$$\sum m < 37\ \text{eV}$$

$$< 23\ \text{eV} \qquad h = 0.5$$

Double beta decay

If neutrinos have Majorana masses.

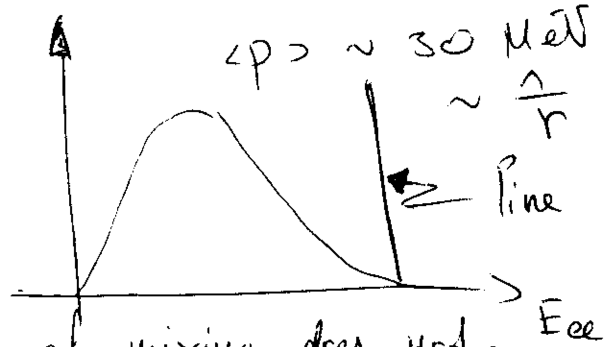




$Z \to (Z+2) + 2e^-$

neutrinoless double β-decay

$$A \propto \left\langle \frac{m_{ee}}{p^2} \right\rangle_{Nucl.}$$



for $m_\nu \ll 30$ MeV

$A \propto m_{ee}$

↑ in the case of mixing does not coincide with mass states (see later).

Best limit:

Heidelberg-Moscow (Gran-Sasso)

enriched isotope (86%) (3 detector)

$$\boxed{{}^{76}Ge \to {}^{76}Se + 2e}$$

$Q = 2038.56$ MeV

8.6 kg·y → 76
(16.9 kg)
→ 10^{25} in future

$T_{1/2} > \underset{(8,6)}{5.1} \cdot 10^{24}$ y

$m_{ee} < 0.68$ eV — 90% CL
< 0.52 eV — 68% CL

for heavy neutr.
$\frac{\epsilon^2}{M_N} < \frac{1}{10^8 \text{ GeV}}$
mixing important

Matrix elements:

Staudt Muto Klapdor (1990)
Hirsch.

Vogel: $\rightarrow \times 2$ $\rightarrow$ $\boxed{m \lesssim 1.5 \text{ eV}}$ (90%)

Mixing

Flavour states ν_e, ν_μ $\neq$ mass states $\nu_1 \nu_2$

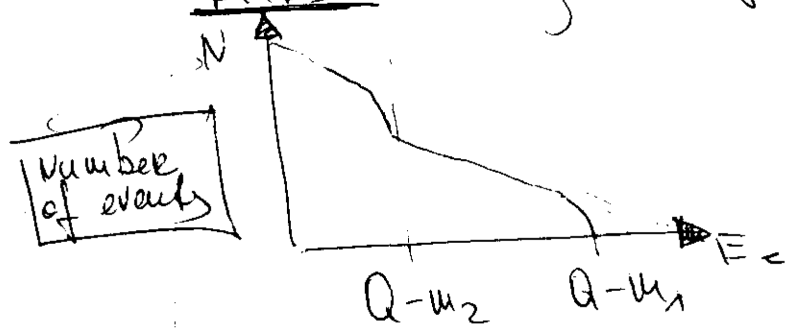
simple 2ν - case:

$$\boxed{\begin{aligned} \nu_e &= \cos\theta\, \nu_1 + \sin\theta\, \nu_2 \\ \nu_\mu &= \cos\theta\, \nu_2 - \sin\theta\, \nu_1 \end{aligned}}$$

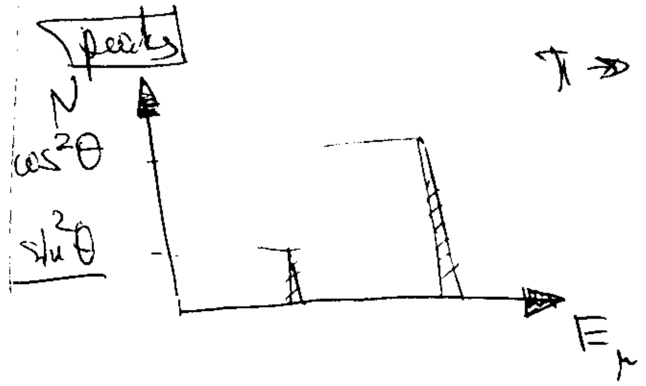
θ is the mixing angle

Kinematical consequences:

Kinks in β - decay spectrum:



Q is the end point of spectrum.



$\pi \to \nu_\mu \mu$

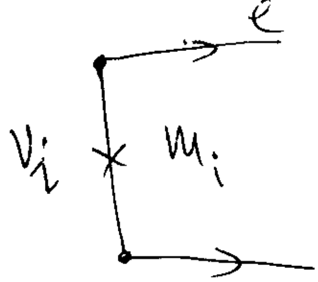
$\pi \to e \nu$

$|U_{ei}|^2 < 5 \cdot 10^{-6}$

$\boxed{\nu\text{- decay.}}$

$$\nu_2 \to \nu_1 \bar{\nu}_1 \nu_1$$

Double β-decay and mixing.



$$\boxed{\nu_e = U_{ei} \nu_1}$$

$$\boxed{\underbrace{m_{ee}}_{\text{effective majorana mass of the electron neutrino}} = \sum_i U_{ei}^2 \cdot m_i}$$

For $m_3 = 20$ MeV

$$U_{ei} \lesssim \sqrt{\frac{m_{ee}}{m_i}}$$ → bound on mixing

$m_{ee} \sim 0.5$ $\quad m_3 = 20$ MeV

0.5 $\quad \underline{U_{e3} < 1.6 \cdot 10^{-4}} \ll V_{ub}, V_{td}$

$2 \cdot 10^{-7}$

$2.5 \cdot 10^{-8}$ $\quad$ i.e. much smaller than corresponding mixing element in quark sector.

Effects of propagation of mixed states

1) Oscillations: in vacuum and in medium with constant parameters (density etc)

2) resonance conversion: in the case of medium with variable parameters.

Resonance conversion $\neq$ enhanced oscillations

another effect.

Oscillations

is the effect related to phases which acquire the neutrino mass states during the propagation:

- Suppose ν_e is produced

$$\nu(0) = \nu_e = \cos\theta\,\nu_1 + \sin\theta\,\nu_2$$

ν_1 and ν_2 are the eigenstates of the Hamiltonian in vacuum:

This means that ν_1 and ν_2 propagate independently: there is no transitions

$$\boxed{\nu_1 \leftrightarrow \nu_2}$$

then only what happens is
the phase which acquire ν_i.

$$\nu_1 \to \nu_1 e^{i\varphi_1}$$
$$\nu_2 \to \nu_2 e^{i\varphi_2}$$

$$\varphi_i \equiv E_1 t - p_1 x \qquad \varphi_1 \neq \varphi_2$$ due to mass difference

correspondingly the neutrino state can be written as

$$\nu(t) = \cos\theta\, \nu_1 + \sin\theta\, \nu_2 \cdot e^{i\Delta\varphi}$$

$$\boxed{\Delta\varphi = \varphi_2 - \varphi_1}$$

(common factor $e^{i\varphi_1}$ is removed; the phase difference important only)

$\Delta\varphi$?

if $p_1 = p_2$ (one can in general take different p_1, p_2)

~~then~~

$$\boxed{\Delta\varphi = (E_2 - E_1)t}$$

or in ultrarelativistic case:

$$E_i \sim p + \frac{m_i^2}{2E} \quad ; \quad \Delta E = \frac{\Delta m^2}{2E}$$

$$\boxed{\Delta\varphi = \frac{\Delta m^2}{2E} t}$$

there is a monotonous increase of phase difference in time

$\Longrightarrow$ oscillations.

$\Delta\varphi = \pi$: (maximal deviation from the initial state

$\Delta\varphi = 2\pi$: the state return in the initial (flavour) state.

1) $\Delta\varphi = \pi$:

$$\nu(\pi) = \cos\theta\, \nu_1 - \sin\theta\, \nu_2$$

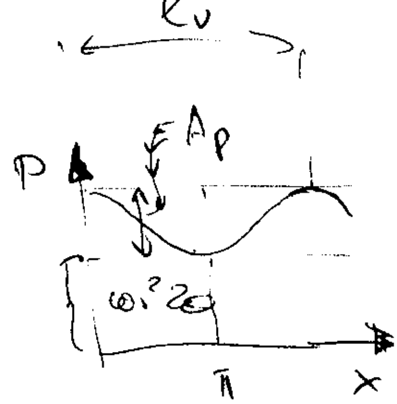
$$\langle \nu_e | \nu(\pi) \rangle = \cos^2\theta - \sin^2\theta = \cos 2\theta$$

the probability to find ν_e:

$$P_\pi = |\langle \nu_e | \nu(\pi) \rangle|^2 = \cos^2 2\theta .$$

the depth os oscillations:

$$\boxed{A = 1 - P_\pi = \sin^2 2\theta}$$



2) $\Delta\varphi = 2\pi$

the distance where $\Delta\varphi = 2\pi$:

$$\frac{\Delta m^2}{2E} t = 2\pi$$

$$\boxed{t = \frac{4\pi E}{\Delta m^2}} = l_\nu \text{ — oscillation length.}$$

$c = 1$

Now we can write the oscillation probability:

$$\boxed{P_{\nu_e \to \nu_\mu} = \underbrace{\sin^2 2\theta}_{\text{depth of oscillations}} \cdot \underbrace{\left(1 - \cos\frac{2\pi x}{l_\nu}\right)}_{\text{oscillating factor}} \cdot \frac{1}{2}}$$

depth of oscillations

oscillating ~~pho~~ factor

To have $\sin^2 2\theta$ for $x = \frac{l_\nu}{2}$

OR:

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \cdot \sin^2 \frac{\pi x}{l_\nu}$$