INTERNATIONAL ATOMIC ENERGY AGENCY
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SMR.762 - 10

Lectures II and III

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

13 June - 29 July 1994

NEUTRINO PHYSICS

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ICTP

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

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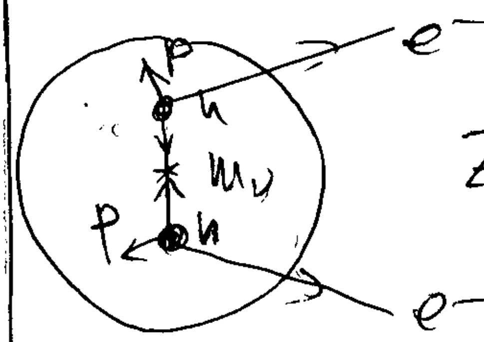
II Majorana neutrinos?

Are neutrino Majorana particles?

Signature → processes $\Delta L = 2$ — If ν are Majorana

$\Gamma \propto m_\nu^2$ ...

Double beta decay:



$P = \frac{m}{p^2}$

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

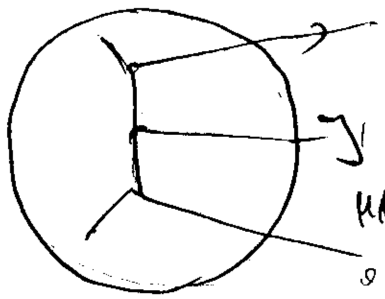
example

$A \sim m$

$m \ll 30$ MeV

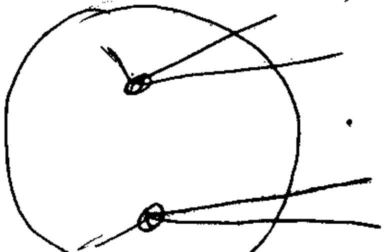
neutrino-less 2β-decay $|\Delta L| = 2$

"MEAVY"



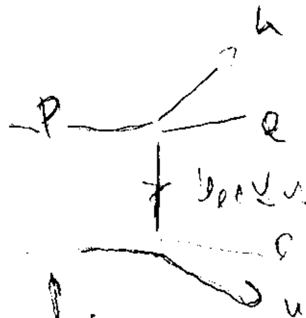
L lepton number is violated spontaneously

Majoron L – spontaneously (although very small)

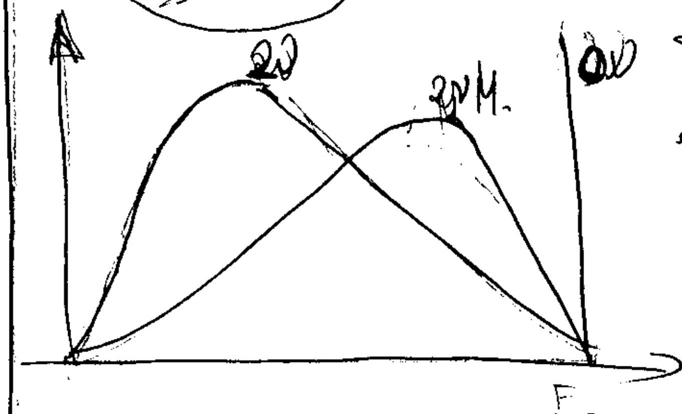


GeNeut

2ν-~~decay~~



light



0ν spectra of 2 electrons

geochemical: $m \lesssim 1.1$ eV Rb, Te · ^{130}Te

E_{ee}

Heidelberg Moscow

m $\quad \boxed{T_{1/2} \gtrsim 3 \cdot 10^{24} \text{ years} \quad m_{ee} < 0.9 \text{ eV} \quad 90\% \text{ CL}}$

0.2

$1.5 \cdot \left(\frac{1.3}{0.9}\right)^2$

• started to discuss the order 10^{-3} eV^2 NEMO, IGEX

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2β decays and BOUNDS on Mixing

$$\nu_e = \sum_i U_{ei} \nu_i$$

[illegible]

m_i

$$m_i \ll 30 \text{ MeV}$$

probs

$$m_{ee} = \sum U_{ei}^2 \, m_i$$

$\to$ BOUND (if one DOMINATES)

$$m_i U_{ei}^2 < 0.9 \text{ eV}$$

10 keV
20 keV
20 keV

$$|U_{ei}|^2 \leq \begin{cases} 10^{-4} & 10 \text{ keV} \\ 10^{-7} & 10 \text{ MeV} \end{cases}$$

Tokyo: $3 \cdot 10^{-3}$

$\to$ m_i - of different sign (CP parity)

- compensation
- $\to$ REAL MASS CAN BE LARGER THAN
- $\to$ DIRAC NEUTRINOS complete COMPENSATION.

$$\nu_e = \cos\theta \, \nu_1 + \sin\theta \, \nu_2$$

HAVE the SAME MASS BUT opposite CP.

HE - experiments

Mixing (Vacuum)

NO MASSES → NO MIXING

SM → redefine of ν states

FLAVOR STATES ≠ MASS STATES

ν_e, ν_μ correspond to ~~Define~~ charge lepton ≈ (CC) interaction; eigenstates of weak interaction

ν_1, ν_2 eigenstate of mass matrix

→ = in flavor basis the mass matrix is not diagonal

→ simplest example 2ν-case

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

$\nu_1, \nu_2 \rightarrow m_1, m_2$

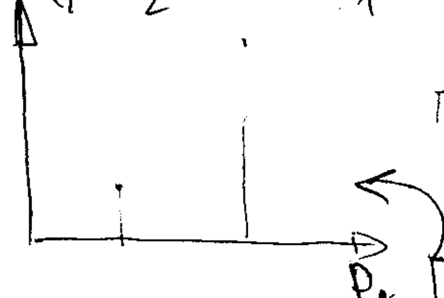
θ – Mixing angle

CONSEQUENCES

kinks

$|U|^2 < 10^{-3}$ at 17 keV

• peaks



$\pi \rightarrow \nu(\mu)$

10^{-5}

e.g. $\pi \to e\nu$ $m_i = 20$ MeV : $|U_{ei}|^2 < 5 \cdot 10^{-6}$

• Decays

$\nu_3 \rightarrow e^+ e^- \nu_e$

$\nu \rightarrow \nu\nu\nu$

$\nu \rightarrow \nu\gamma$

Mixing in more details

BEFORE: see-saw for 1 generation

VACUUM: → induced by mass matrix

– quak

$\begin{pmatrix} \nu \\ e \end{pmatrix}$

Direct

BOUNDS of mixing from searches

• Gives stringent bounds in large mass region

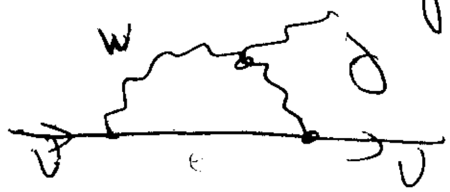
• more sensitive to small mixing are

• PROPAGATION of mixed neutrinos → oscillation of flavor

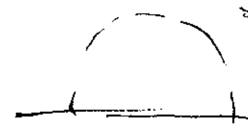
Next lecture

Electromagnetic properties

- INTERACTIONS with γ in high orders



scalar



→ CHANGE OF HELICITY

in SN + ν_R

→ external line

Dipole moment
ANOMALOUS DIPOLE MOMENT

· HELICITY flip.

$\mu \sim m_\nu$
but the coeff can be different

→ $\mu \propto m_\nu$ (IN GENERAL)

- IF CHANGE OF HELICITY IN THE INTERNAL LINE → ENHANCEMENT

but the MASS will be LARGER → new m-bound

$\boxed{\text{MAJORANA}}$

$\mu = e \cdot 25$

→ μ of ~~the~~ MAJORANA Neutrinos

Motivation $\boxed{\mu = 0}$

$\langle \varphi | \hat{\mu} | \psi \rangle^T$
CC CC

~~XXXX~~

→ NONDIAGONAL MAGNETIC MOMENT ν_2

~~XXXX~~ $\nu_{\alpha L}^T C \sigma_{\mu\nu} \nu_{\beta L} F^{\mu\nu}$

ψC^+

→ SM:

$$\mu = \frac{3 G e m_\nu}{8\sqrt{2}\pi^2} \sim 3.2 \cdot 10^{-19} \mu_B$$

$\boxed{\text{IN PLASMA}}$

$\boxed{\mu_B = \frac{e}{2m_e}}$

$$\frac{\mu}{m_\nu} = e\frac{3G_F}{8\sqrt{2}\pi^2} \sim e \cancel{\frac{g^2}{8 M_W^2}} \frac{3}{8\pi^2 V^2}$$

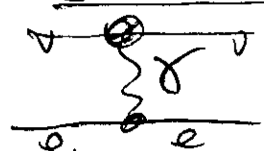
MASS ⟷ MAGNETIC MOMENT.

→ MASS – μ_ν – relation

$$\boxed{\delta m = \frac{\mu_\nu}{e}\Lambda^2} \cdot A$$

PHENOMENOLOGY OF μ_ν

→ ν_e e - scattering



reactors

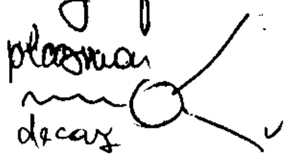
At low q^2 can dominate over electroweak

$\mu \lesssim 2 \cdot 10^{-10} \mu_B$

new exp → $2 \cdot 10^{-11} \cdot \mu_B$

→ ASTROPHYSICS

- cooling of stars



$\mu < 3 \cdot 10^{-12} \mu_B$

(white dwarfs, red giants)

→ SN. Dirac $\mu \lesssim 10^{-13} \mu_B$

→ EFFECTS IN PRIMORDIAL MAGNETIC FIELDS DIRAC $10^{-11} \mu_B$

→ solar neutrinos time variations of signals

effect ~ 1 if $B \gtrsim 10^5$ G...? ?

→ SN neutrinos

→ ionization of interstellar medium (intergalactic medium)

Sciama:

several 10^{-14}

$\nu \to \nu \gamma$ → give ionization of

n_e

CONCENTRATION OF ELECTRONS IN CLOUDS

$m_2 = 27.8 - 29$ eV

$m_1 < 3$ eV

$\tau \sim (1 \div 3) \cdot 10^{23}$ s

$E_\gamma = 13.9 - 14.534$ eV

I

1

PROPAGATION OF "MIXED" NEUTRINOS IN VACUUM AND MEDIUM

DERIVATION → "PHYSICAL" WHICH ALLOW TO UNDERSTAND THE PHENOMENA

source — — — detector

ATTENUATION.

- Sun
- SN
- Atmosphere
- Long base line experiments

- inelastic scattering
- absorption

- High energies
- High densities near SN. core.
- Early universe.

- $\Gamma_{inel.} \ll 1$ – typically

⇒ propagation in $\boxed{\text{TRANSPARENT}}$ MEDIUM → photon in case of transparent MEDIUM:
→ refraction phenomena
⇒ neutrino refraction phenomena.

- AND IN VACUUM

Very simple.

1. ~~ultrarelativistic~~
$$\frac{m_\nu}{E} \lll 1$$
⇒ one can neglect spin flip effects (IN vacuum)
omit spinor structure.

2. $E \ll m_{\nu}^{2}/m_{\nu}$ →
neglect the effect OF inelastic scattering.

3. 2ν – mixing case

All this can be justified.

As ...

⇒ No absorption → transition in flavor space.

enough follow physics

- can be justified if consider more precise tools
- enough to get the results and follow the physics

EVOLUTION EQUATION.

$$i \frac{d\nu}{dt} = E\nu \approx \left(p + \frac{m^2}{2E}\right)\nu$$

Schrödinger Pic.

ultrarelativistic

solution → plane wave

2 neutrinos ν_f with MASS MATRIX M in flavor space.

$$\nu_f = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$\boxed{i \frac{d\vec{\nu}}{dt} = \left(\hat{p} I + \frac{M^2}{2E}\right)\vec{\nu}.}$$

can be absorbed in redefinition.
→ since the respective change of w.φ is important.

ON DEFINITION.

M is diagonalized by $S(\theta)$:

$$S^+(\theta) M S(\theta) = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

$$\nu_f = \hat{S}(\theta_0)\nu$$

$$\nu = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

the state with definite m

we can express M^2 in terms of θ and m_i:

$$M^2 = S(\theta) \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} S^+(\theta)$$

evolution equation

$$\boxed{i \frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}$$

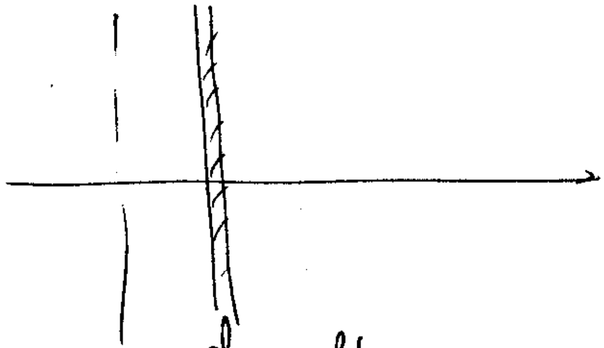
MATTER EFFECT

- REFRACTION ≡ FORWARD ELASTIC SCATTERING
TRANSPARENT MEDIUM
(≡ inelastic scatt. can be NEGLECTED)

SEVERAL WAYS TO REDUCE THE effect:

1) CHANGE OF WF due to scattering in slab

$d\Psi = ?$ due to scatteri



$dx \sim dt$

e^{ipnx}

$d\Psi = \Psi (n-1) p\, dx$

↑ Refraction index

$$n - 1 = \frac{2\pi f(0)\, n}{p^2}$$

CM

$d\Psi = \sqrt{2} G_F n \Psi$

2). MATTER effect as → potential →

$V = \sqrt{2} G_F n$

3). ~~effect~~ Dirac equation + interact with medium

$\frac{G_F}{\sqrt{2}} (\bar{\nu} \gamma^\mu (1+\gamma_5) \nu)(\bar{e} \gamma^\mu (1+\gamma_5) e)$

$\rightarrow \frac{G_F}{\sqrt{2}} \langle \Psi | \bar{e} \gamma^\mu (1+\gamma_5) e | \Psi \rangle$

$\rightarrow \langle \Psi | \bar{e} \gamma^0 e | \Psi \rangle = \sqrt{2} G_F n_e$

4) ~~Green~~ AS correction to self energy

Green function in medium

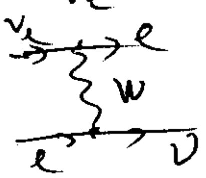
$$V \equiv \begin{pmatrix} V_e & 0 \\ 0 & V_\mu \end{pmatrix}$$

Di

$$i\frac{d\psi}{dt} = \left(\frac{M^2}{2E} + V\right)\psi$$

Difference is important:

$$V_e - V_\mu = \sqrt{2}\, G_F\, n_e .$$



explicitly:

$$\boxed{i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{2}G_F n_e - c_2 & s_2 \\ s_2 & c_2 \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}$$

$$c_2 \equiv \frac{\Delta m^2}{4E}\cos 2\theta$$

$$s_2 \equiv \frac{\Delta m^2}{4E}\sin 2\theta$$

Wolfenstein equation

How to solve EQ.

(1) INTRODUCE

EIGENSTATES OF NEUTRINOS

$\equiv$ EIGENSTATES ~~EQ~~ of H.

$\nu_{im} \longleftrightarrow$ relation with ν_f

(2). FIND EQUATION for ν_{im}

(3) SOLVE EQ for ν_{im}

(4) USING ~~relation~~

$\nu_m \Longleftrightarrow \nu_f$

find solution for ν_f

* Solution of the equation

① → NEUTRINO EIGENSTATES IN MATTER:

$$\boxed{\nu_m = \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}}$$ → states which DIAGONALISE THE HAMILTONIAN

introduce $\nu_f \to \nu_{im}$

$H(n_e)$:

$$\boxed{\nu_f = S(\theta_m)\,\nu_m}$$

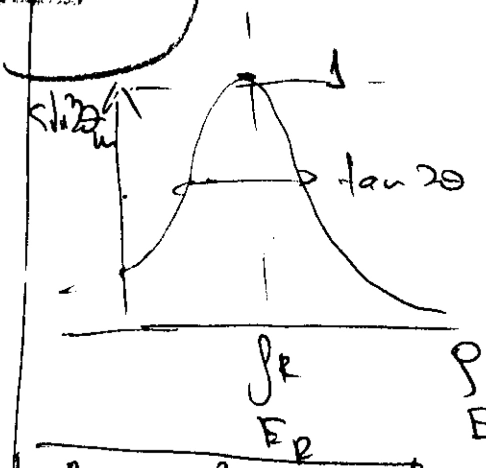
where
$$S(\theta_m) = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix}$$

$$S(\theta_m)^{+} H\, S(\theta_m) = H^{diag} = \begin{vmatrix} H_{1m} & 0 \\ 0 & H_{2m} \end{vmatrix}$$

$\left.\begin{matrix} H_{1m} \\ H_{2m} \end{matrix}\right\}$ - eigenvalues of ν in medium
≡ energy levels

$$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - \sqrt{2}\, G_F n_e \frac{2E}{\Delta m^2}}$$

θ_m is mixing angle in matter.



$$\boxed{n_e^R = \frac{\Delta m^2}{2E} \frac{\cos 2\theta}{\sqrt{2}\, G_F}}$$

resonance

OBSERVATIONS

→ θ_m - depends on n_e.

→ $\boxed{\nu_m = S^{+}(\theta_m)\,\nu_f}$.

⇒ θ_m determine flavor composition of eigenstate

→ as This flavor composition ~~CHANGES wi~~ depends on density

VACUUM:

$\boxed{\theta_m = \theta}$ const $\quad \boxed{\dot{\theta}_m = 0} \leftarrow$ no $\nu_{1m} \to \nu_{2m}$ $\quad n_e = 0$

$$i\frac{d\nu}{dt} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \nu$$

$\nu_{im} = \nu_i$

ν_{im} - ARE the states ~~with~~ definite MASSES

flavor composition of ν state is const

in VACUUM ν_i ≡ ~~STATES~~ NEUTRINOS WITH DEFINITE MASSES ARE THE EIGENSTATES

$$\boxed{H_i = \frac{m_i^2}{2E} \qquad \psi = e^{i\frac{m_i^2}{2E}t}}$$

→ PROPAGATE INDEPENDENTLY ν_i

→ PHASE CHANGE

- (admixture conserved) - θ.
- flavor is conserved

ν_e

$$\boxed{|\nu(t)\rangle = \cos\theta \, |\nu_1\rangle + \sin\theta \, |\nu_2\rangle e^{-\frac{\Delta m^2}{2E}t}}$$

ONLY effect is phase CHANGE

MEDIUM WITH CONSTANT DENSITY

SEE NEXT PAGE

$\theta_m \neq \theta$

$\dot{\theta}_m = 0$.

THE ~~evolution~~ eq for ν_{im} are splitted

ν_{1m} _ ν_{2m} PROPAGATE INDEPENDENTLY — no change of ADMIXTURE

flavor of ν_{im} is fixed

solution:

oscillations which CHARACTERISED BY THE DEPTH

$$\boxed{\begin{array}{l} \bullet \ \sin^2 2\theta_m \\ \bullet \ \text{length: } l_m = \dfrac{2\pi}{H_1 - H_2} \end{array}}$$

- admixture conserved
- flavor is conserved

$\sin^2 2\theta_m - n_e, E$!

→ RESONANCE ENHANCEMENT OF oscillat.

At E_R : $\sin^2 2\theta_m$

7 (8)

2. Evolution equation for eigenstates:

$$i \frac{d\nu_m}{dt} = \left(H^{diag} - i S^{+}(\theta_m) \frac{dS(\theta_m)}{dt}\right)\nu_m$$

substituting:

$$\boxed{i \frac{d}{dt}\begin{pmatrix}\nu_{1m}\\ \nu_{2m}\end{pmatrix} = \begin{pmatrix}H_{1m} & i\dot{\theta}_m\\ -i\dot{\theta}_m & H_{2m}\end{pmatrix}\begin{pmatrix}\nu_{1m}\\ \nu_{2m}\end{pmatrix}}$$

EIGENSTATES OF $\hat{H}$ DO NOT DIAGONALIZE

$$\dot{\theta}_m \equiv \frac{d\theta_m}{dt}$$

if Ψ_{im} are solution .. of the
→ combination

3 ~~...~~ = then coming back to flavor states
$\nu_{im} \Rightarrow \nu_f$ (θ_m)

if $\nu_i(0) = \nu_e$

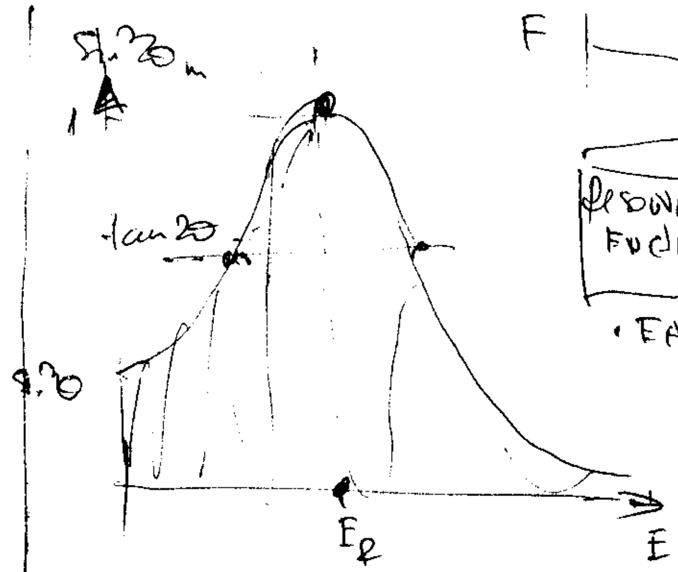
3. $$\boxed{|\nu(t)\rangle = \cos\theta_m^0\, \Psi_1(t)\, |\nu_{1m}\rangle + \sin\theta_m^0\, \Psi_2(t)\, |\nu_{2m}\rangle}$$

mixing in initial moment

solution of the equation for

solutions of eq. normalized in $\Psi_i(0) = 1$

$$P_{\nu_e \to \nu_e} = \left|\cos\theta_m^f \cdot \cos\theta_m^0\, \Psi_1(t) + \sin\theta_m^f \sin\theta_m^0\, \Psi_2(t)\right|^2$$



F — continuous spectrum

E

resonant enhancement of oscillations

• EARTH.

CONDITION: OF RESONANCE

$$\cos 2\theta = \sqrt{2} G_F n_e \frac{2E}{\Delta m^2}$$

VARYING DENSITY:

$\dot{\theta}_m \neq 0$ — MIXING CHANGES ALONG ν-trajectory.

* suppose:

$$\boxed{\dot{\theta}_m << |H_2 - H_1|}$$

ADIABATICITY CONDITION

$n(x)$ - changes slowly

⇒ No $\dot{\theta}_m$ CAN BE NEGLECTED.

AS in n = const case

- $\nu_{1m} \leftrightarrow \nu_{2m}$ transitions CAN BE NEGLECTED
- ν_{im} PROPAGATE INDEPENDENTLY

solution AS IN n = const case

$$\psi_i = e^{iH_i t}$$

~~$\langle \nu_e | \nu(t) \rangle$~~ = But in contrast with uniform medium FLAVOR OF ν_i STATE CHANGES IN TIME

$$\theta_m = \theta_m(t)$$

IN GENERAL

- flavor of ν_{im} is changed
- $\dot{\theta}_m \neq 0 \Rightarrow \nu_{1m} \Leftrightarrow \nu_{2m}$

THERE ARE TRANSITIONS BETWEEN THE EIGENSTATES

$$\dot{\theta}_m \propto \dot{n}$$

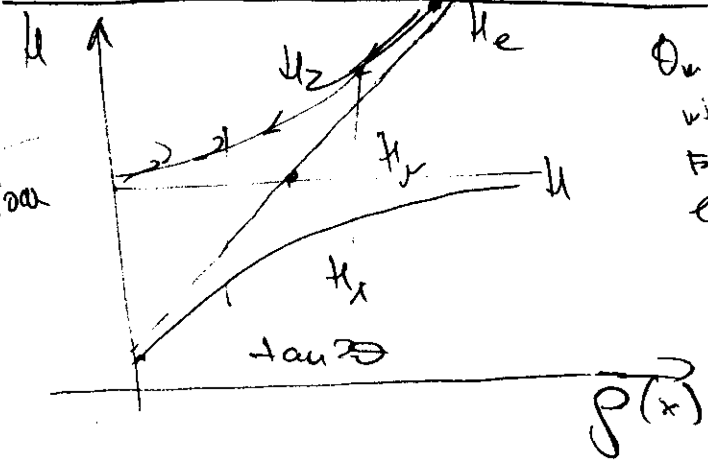
INITIAL MIXING ≠ FINAL MIXING

RESONANT CONVERSION MSW

$$\begin{vmatrix} M_e & A \\ A & M_\mu \end{vmatrix}$$

IN TERMS OF EIGENVALUES

NO TRANSITION



θ_m = max

WHE DIAGONAL ELEMENS ARE EQUA

AT THE SAME LEVEL.

MSW – CHANGE OF MIXING

Oscillations = PHASE INTERPLAY

~~...~~

ADIABATICITY VIOLATION.

- θ_i can not be neglected !!
- there are the $\nu_{1m} \leftrightarrow \nu_{2m}$ (jumps between the levels) ⇒ in RESONANCE

$|\nu_2\rangle \to |A_{21}| \, |\nu_1\rangle + \cancel{A_{22}} \, (1-A_{21}) |\nu_2\rangle$

if A_{12} – is the amplitude of transition

the AVERAGE SURVIVAL PROBABILITY

$$\cancel{P} = P = \frac{1}{2} - \left(\frac{1}{2} - P_{12}\right)\cos 2\theta_0 \cos 2\theta_f$$

$$w \quad P_{12} = |A_{12}|^2$$

$\frac{1}{2} - \cos 2\theta_0 \cos 2\theta_f$

1 – in RESONANCE

Not so Deep

very strong adiab. violatio $\nu_e \to \nu_e$

P_{12} can be estimated

$$\cancel{\frac{\dot\Theta_m}{H_1 - H_2} = \varkappa_R} \qquad \frac{|H_1 - H_2|}{\dot\Theta_m} = \varkappa_R$$

(in crossing point)

adiabaticity parameter

$$\boxed{P_{12} \sim e^{-\frac{\pi \varkappa_R}{2}}}$$

Landau-Zener Stuckelberg probability (transition between two levels)

introduce by uncertainty pri

$P \to 0$

Quantum mechanical task

$$\varkappa_R \equiv \frac{\Delta m^2}{2E} \frac{\sin^2 2\theta}{\cos 2\theta \left(\frac{dn_e}{n_e\, dr}\right)}$$

l_n

$P \sim 1$

$\Delta E \cdot \Delta t \sim 1$

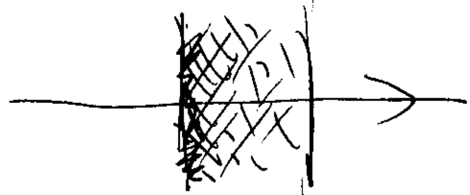
$$\Delta t = \frac{n_e}{\frac{dn}{dt}} \cdot \tan\theta$$

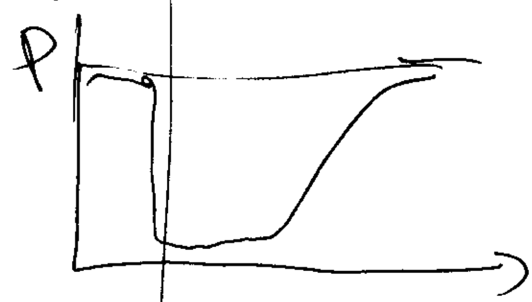
$$\Delta E = \frac{\Delta m^2 \cdot \sin\theta}{2E}$$

$\varkappa_R =$

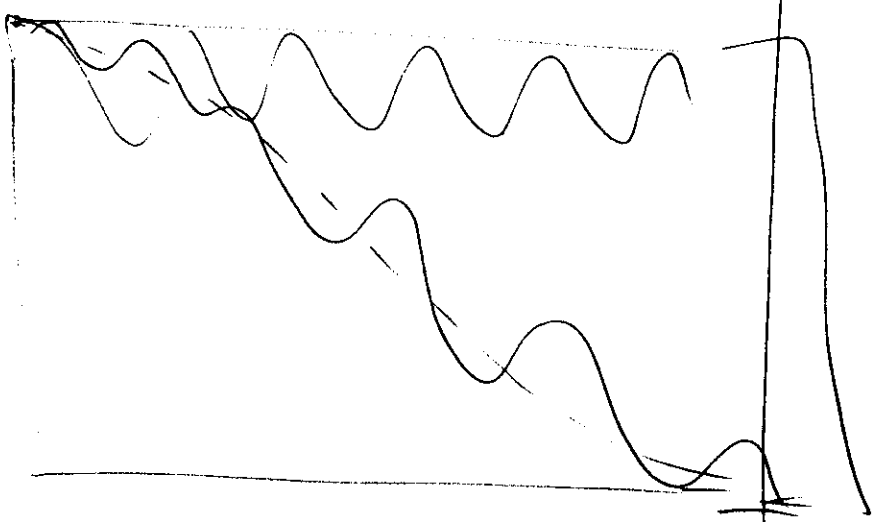
$P \sim \frac{\quad}{\Delta E}$

Resume:





- Oscillations
- Resonant conversion



Next → applications

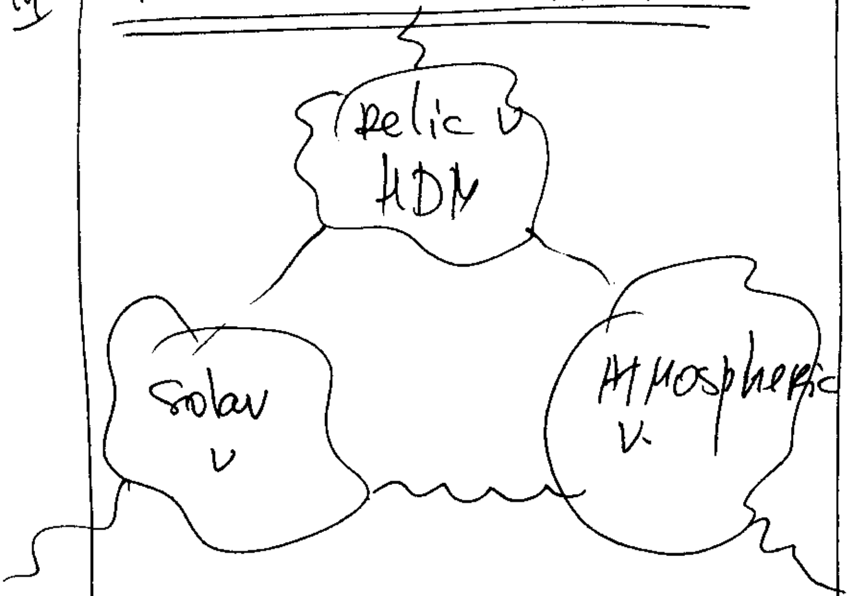
- Generalization
  - Mixing
  - Level splitting
  - level crossing

Mixing → by matter
→ gravitational interaction

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \qquad \begin{pmatrix} \nu_{eL} \\ \nu_{\mu R} \end{pmatrix} \begin{pmatrix} \cdot & \mu B \\ \mu B & \cdot \end{pmatrix}$$

Oscillation → spin-precession
conversion → resonant spin-flip

III NEUTRINO ANOMALIES

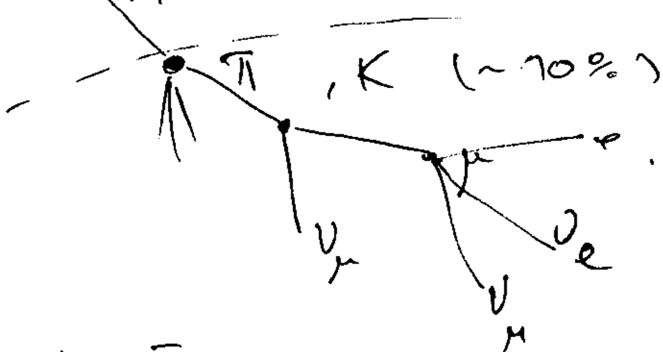


- oscillations at ~~[illegible]~~ Los Alamos.
- 2β - decay.
-
⋮

ATMOSPHERIC NEUTRINOS

produced in the atmosphere:

P, N ← cosmic rays

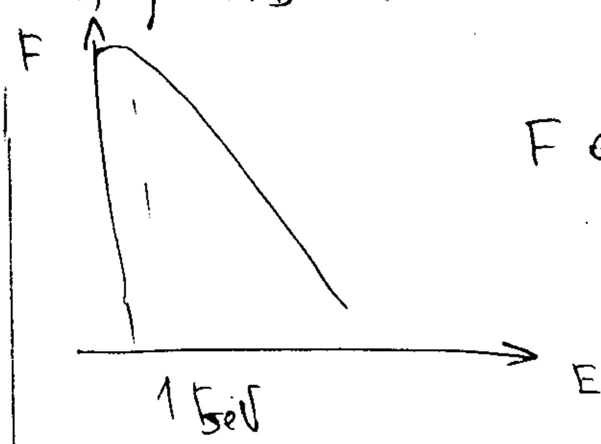


$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

roughly

(absorption

- calculation of absolute values of fluxes
- normalization to observed flux of μ and e.



$F \propto E^{-2.7}$

• Absolute fluxes ~ 30% accuracy

Ratio of ν_μ / ν_e ~ < 5%

• Flux ? ← absolute value ?

$p^+ \longrightarrow \pi^+$

π^+ dominate over π^-?

2 < 1 GeV

1.5

$F = 40 - 80 \ \frac{1}{m^2\, sr\, s}$

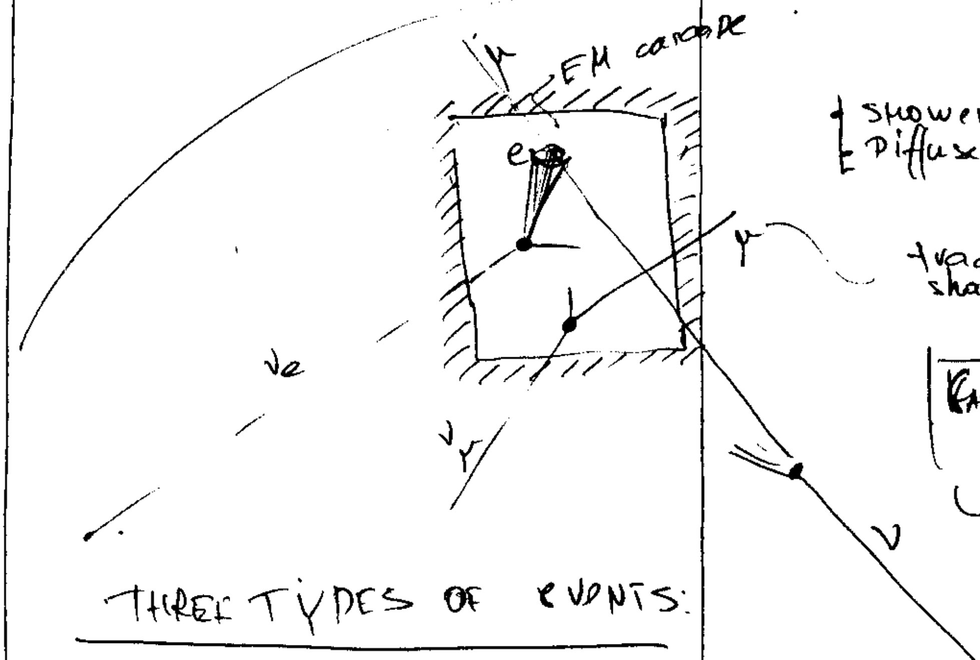
1 GeV

Bin 1 MeV

Detection.

UNDERGROUND installations:

KAMIOKANDE	+
IMB	+
Frejus	−
NUSEX	−
BAKSAN	−
SOUDAN	+/−
MACRO	? ← ANOMALY



SHOWERS
Diffuse RINGS.

track
sharp rings

KALIBRATION:
identification
is OK.

THREE TYPES OF EVENTS:

1) CONTAINED events, i.e. INTERACTION inside THE INSTALLATION

QUASIelastic scattering.

$E_\nu \sim 3 - 10$ GeV

$E = 0.2 - 1.5$ GeV

2) Upward going muons. 20 - 100 GeV

(a) stopping (decay in the detector) 50-300 GeV.

(b) throughgoing.

$E_\nu =$

Results:

(1) DOUBLE RATIO:

$$R(\mu/e) = \frac{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{exp}}{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{\text{theory MC?}}}$$

NO energy AND ANGULAR dependence OF suppression (?)
→ AVERAGED oscillation effect.

$R(\mu/e) = 1$ (if our theory is OK)

Observation

$$\boxed{R(\mu/e) \triangleq 0.6.}$$

KAM.
IMB
SOUDAN.

KAMIOKANDE:
$0.60^{+0.06}_{-0.05}$

Deficit of ν_μ ($\bar{\nu}_\mu$) ?
OR
excess of ν_e ($\bar{\nu}_e$) .

SOUDAN
$0.64 \pm 0.17 \pm 0.09$

- no effect in Frejus, NUSEX, MACRO? } H.E.
- NO effect in MEASUREMENTS OF UPWARD going muons.

ANOMALY AT LOW ENERGIES ?

INTERPRETATION:

Oscillations: $\nu_\mu \Rightarrow \nu_\tau$

$$\boxed{\begin{aligned} \Delta m^2 &\sim (0.4-3)\cdot 10^{-2}\, eV^2 \\ \sin^2 2\theta &= 0.5-0.6 \end{aligned}}$$

in this region one can reconcile all the DATA.

- proton decay
$p \Rightarrow e^+\nu\nu$
(excess of e)

$M_{Atm} = 0.1\,eV$

$\nu_\mu \Leftrightarrow \nu_e$ ← matter effect.

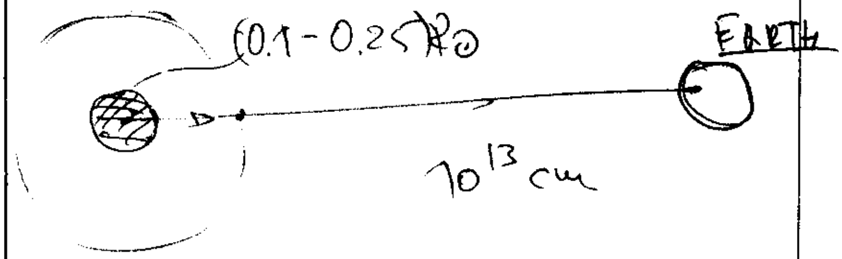
$\Delta m^2 = (0.5-2)\cdot 10^{-2}\, eV^2$
$\sin^2 2\theta \simeq 0.4 - 0.6$

LONG BASELINE EXPERIMENTS

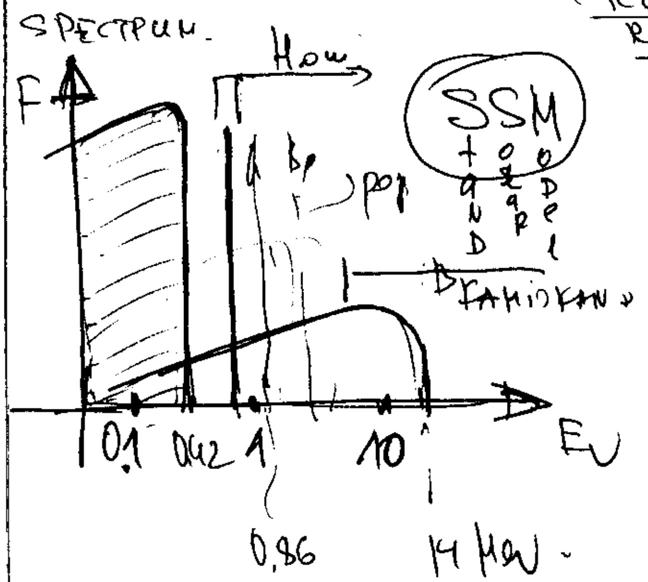
Recent H.E. like, ewa!

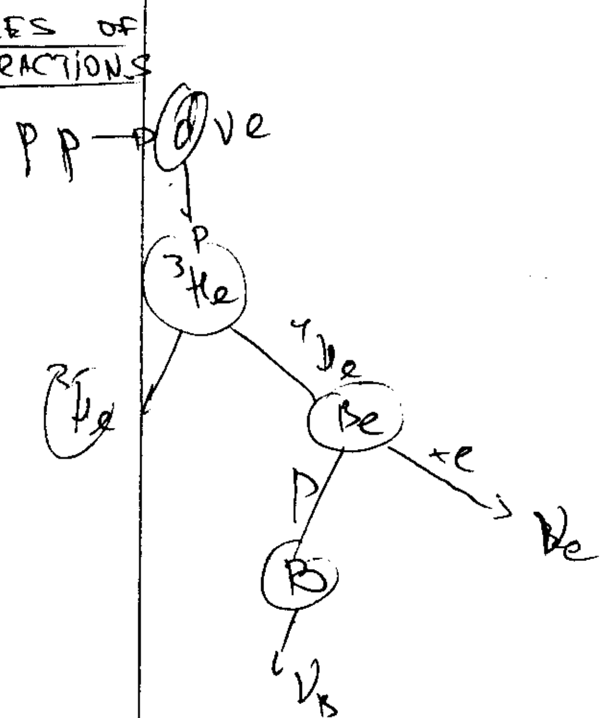
⑤ St

1) SOLAR NEUTRINOS



FLUXES





DATA | 4 Experiments |

(1) HOMESTAKE (DAVIS)

$$\nu_e + {}^{37}Cl \to {}^{37}Ar + e$$

counts number of Ar.

- $E_{th} = 0.81$ MeV

$$R_{Ar} = \frac{Q_{Ar}}{Q_{Ar}^{SSM}} = \frac{2.55 \pm 0.25}{8.} = 0.32 \pm 0.03$$

1972. MORE 20 YEARS

- time variations ?

KAMIOKANDE.

REAL TIME EXPERIMENT

$\boxed{\nu e \rightarrow \nu e}$

SCATTERING.

MEASURE: recoil electrons (Čerenkov RADIATION)

→ $E_{th} \sim 7 - 7.5$ MeV

- HE – BORON neutrinos

→ Direction = proven that (ANGULAR distribution of the events) – peaked out of THE SUN.

→ $\boxed{R_{\nu_e} = \frac{F_{exp}}{F^{B}_{SSM}} = 0.50 \pm 0.04 \pm 0.06.}$

→ NO DISTORTION OF THE ENERGY SPECTRUM.

→ NO TIME VARIATION.
- seasonal
- DAY – NIGHT.

SAGE
GALLEX.

RADIOchemical.

$\boxed{\nu_e + {}^{71}Ga \rightarrow {}^{A}Ge + e}$

counts of number of

$E_{th} = 0.233$ MeV pp.

$R_{Ga} = \frac{Q^{exp}_{Ge}}{Q^{SSM}_{Ga}} = \frac{79 \pm 12}{131} = 0.60 \pm 0.09$ GALLEX

$\frac{74 \pm 21}{131} = 0.56 \pm 0.16$

VACUUM CASE

ν_μ admixture appears in the beam.

- admixtures are fixed but the phase between ν_α and is changed $\Rightarrow$ oscillations.

- periodic.

$$\frac{\Delta m^2}{2E} t = 2\pi \quad \to \text{back to the initial state}$$

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

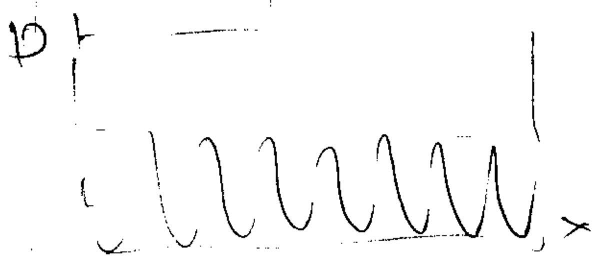
(period of oscillations)

$$P_{\nu_e \to \nu_\mu} = |\langle \nu_\mu | \nu(t) \rangle|^2$$ – probability to find ν_μ

Depth of oscillations:

$$\langle \nu_\mu | \nu(t) \rangle = \sin^2 2\theta$$

$$\boxed{P = \underbrace{\sin^2 2\theta}_{\text{depth}} \cdot \sin^2 \frac{\pi x}{l_\nu}}$$



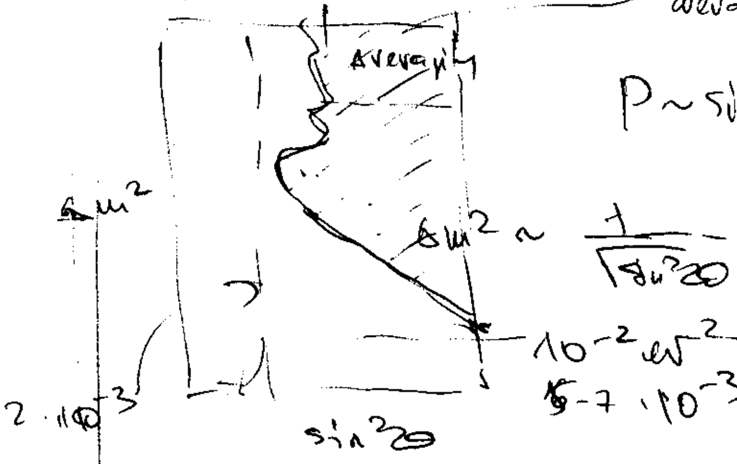
Oscillation $\Rightarrow$ periodical process of transition of one neutrino into another
- stipulated by monotonous PHASE CHANGE between the eigenstates

6

I) $d \ll \ell_\nu$: averaging overall oscillat

$$P \sim \frac{1}{2}\sin^2 2\theta$$

$$P \sim \sin^2 2\theta \cdot \left(\frac{\pi x}{\ell_\nu}\right)^2 \propto \sin^2 2\theta\, (\Delta m^2)^2$$



accuracy of measurement

long base li

SOLAR NEUTRINO PROBLEM

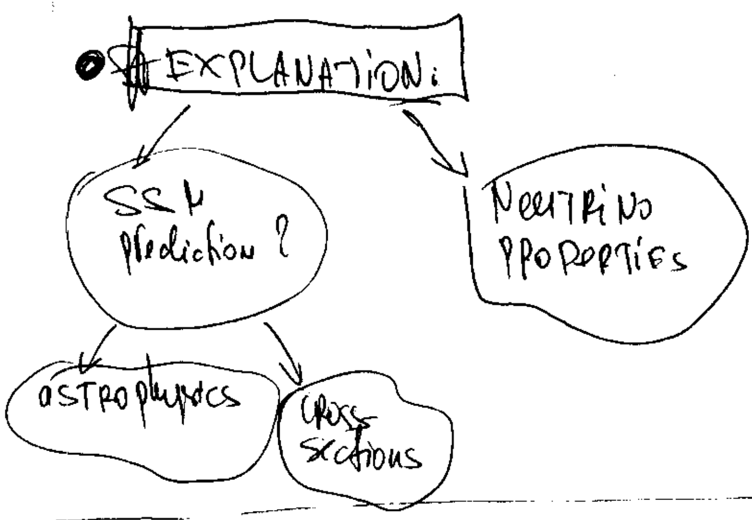
ON THE surface:

(1) ALL SIGNALS ARE SMALLER THAN PREDICTIONS of SSM

(2). THE SUPPRESSION IS DIFFERENT IN DIFFERENT EXPERIMENTS

$$\boxed{\frac{R_{Ar}}{R_{\nu e}} = 0.64 \pm 0.11}$$

in



MODEL INDEPENDENT ANALYSIS

(I) TAKE F_B AS MEASURED BY KAM.

$F_B^{(KAM)}$ → CALCULATE the signal in HOMESTAKE experiment

$\Rightarrow Q_{Ar}^{(KAM)} = 3.15 \pm 0.45$ SNU

$Q_{Ar} = 2.55 \pm 0.25$ SNU – SMALLER !

17%

$$\boxed{Q_{Ar}^{exp} < Q_{Ar}^{B}}$$! ← CONTRADICTION. → 1 SNU

WHERE ARE Be NEUTRINOS ? pep, CNO ?

II Luminosity of ☉

⟹ ALLOW TO NORMALIZE
pp - neutrino flux

HYDROGEN BURNING

CYCLE:

$$4p + 2e^- \to {}^4He + 2\nu_e + \underset{26.7\ \text{MeV}}{Q}$$

• TERMAL EQUILIBRIUM:

$$\boxed{L_\odot = Q_N} + L_\nu$$

number of the nuclear chains: per second

$$Q_N = N \cdot \quad N = \frac{L_\odot}{Q - 2\bar{E}_\nu}$$

$\bar{E}_\nu \sim 0.5$ MeV

$$F_\nu = \frac{2 L_\odot}{Q - E_\nu} \simeq F_{pp}$$

$$Q_{Ge} \sim (70-75)\ \text{SNU}$$

$$Q_{Ge}^{exp} = 71 + \underbrace{\frac{1}{2} 14}_{\text{Boron neutri}} \approx 78\ \text{SNU}$$

signals in Ga-experiments are at the level of minimal signal estimated from Solar luminosity

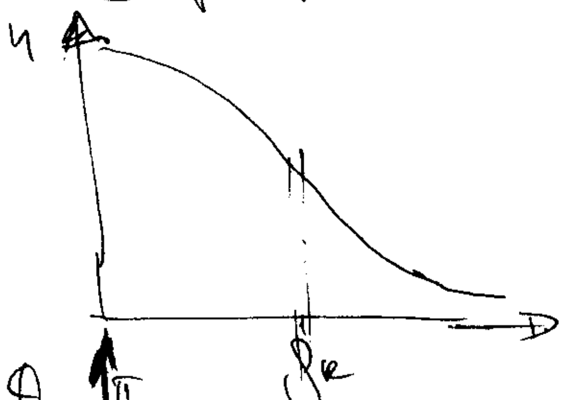
⟹ confirm strong suppress. of all other fluxes

$$|\nu(t)\rangle = \cos\theta_m^0\, |\nu_{1m}\rangle + \sin\theta_m^0\, |\nu_{2m}\rangle\, e^{i(H_2-H_1)t}$$

FLAVOR CHANGES ~~Acco~~ θ_m according to CHANGE OF n_e

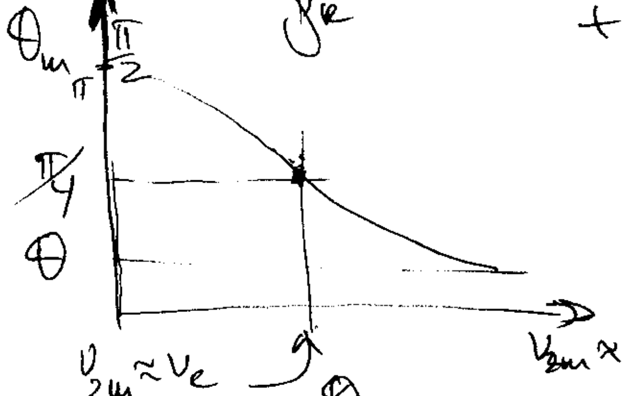
→ Result in DRASTICAL CHANGE OF picture.

• E is fixed.



RESONANCE CONDITION:

$$n_e^R = \frac{\Delta m^2 \cos 2\theta}{E\, 2\sqrt{2} G_F}$$



$\nu_{1m} \approx \nu_e$ maximal mixing ν_μ at RESONANCE DENSITY
equa.

$\rho_0 \gg \rho_R$

$\nu_e \approx \nu_{2m}$

ADIABATIC: $\nu_{2m}(t) \to \nu_{2m}(0) \approx \nu_2 \approx \nu_\mu$

No oscillation Depths ≈ 0.

$\langle \nu_e | \nu_2 \rangle = \sin\theta$

$\boxed{P_{\nu_e \to \nu_\mu} = \sin^2\theta}$ — STRONG TRANSFORMATION

pure CONVERSION.

Best description of DATA

(1). $F_B \sim 0.41\, F_B^{SSM}$

(2). The fluxes of Be-, N, O-, p-e-p- neutrinos are strongly suppressed

(3). pp-flux is unsuppressed or suppressed very weakly.

→ there is an additional contribution to E_{H} signal $\approx 0.09\, F_{SSM}$.

If the exp. DATA are true, ~~there~~ then can not be explained by astrophysics.

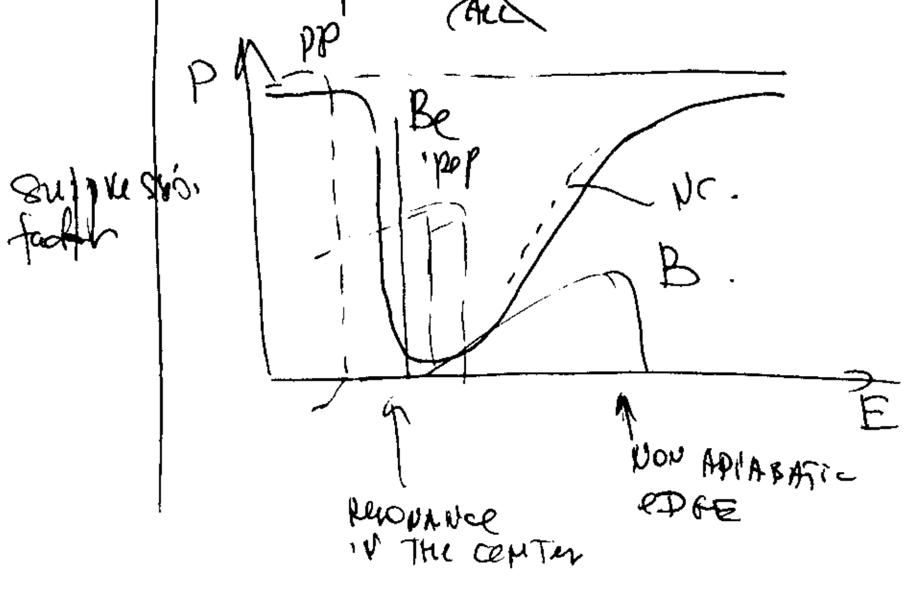
→ ENERGY DEPENDENCE OF SUPPRESSION

- NO suppression at low energies (pp)
- STRONG suppression in the INTERMEDIATE REGION Be, pep NO.

$\approx \frac{1}{2}$ in high energy part.

RESONANT FLAVOR CONVERSION: IN MATTER OF THE SUN

CAN REPRODUCE ALL THESE FEATURES:

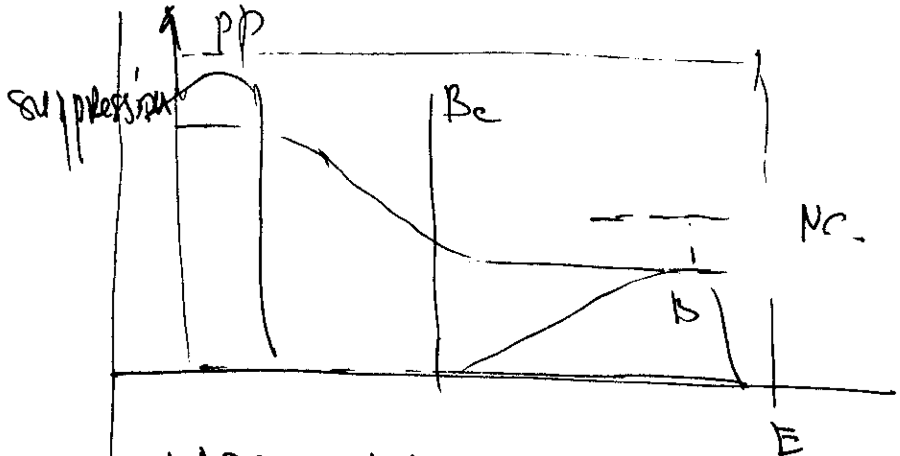


SMALL MIXING.

→ $\Delta m^2 = (6 \pm 2) \cdot 10^{-6}\ eV^2$

$\boxed{\sin^2 2\theta = 10^{-3} - 10^{-2}}$

TAKING INTO ACCOUNT THE UNCERTAINTIES IN B-NEUTRINO flux

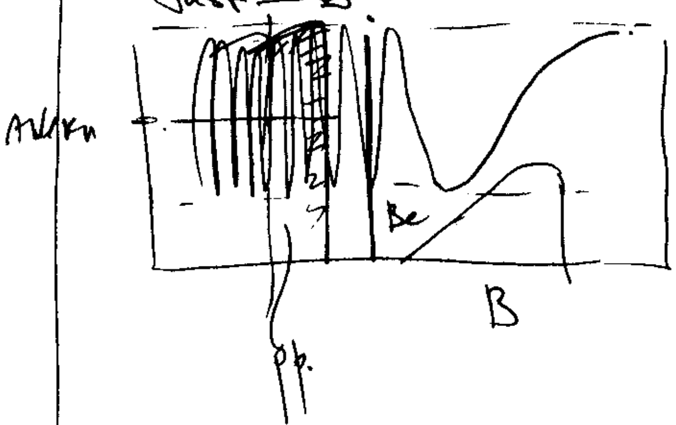


LARGE MIXING SOLUTION.

$$\boxed{\begin{aligned} \Delta m^2 &= (0.3-3)\cdot 10^{-5}\, eV^2 \\ \sin^2 2\theta &= (0.3-0.9) \end{aligned}}$$

* Long length ~~RANGE~~ vacuum oscillation.

~~on~~ "Just — so"



~~the~~ fit is worthless

$$\boxed{\begin{aligned} \Delta m^2 &= (0.3-1)\, 10^{-10}\, eV^2 \\ \sin^2 2\theta &= (0.75-1) \end{aligned}}$$

$$\boxed{M_{\odot} = (2-3)\cdot 10^{-3}}$$

MDM

MACHOS:

- NO NOW CANDIDATES
- MAY SOLVE GALACTIC PROBLEM BUT NOT LARGE STRUCTURE
- $n_B^{vis} \simeq n_B^{total}$?

- Best fit of DATA:

  15 − 30 % of HDM

  + CDM

Implications to particle physics

$$\boxed{m_\odot = (2-3)\, 10^{-3}\ eV}$$

see – saw:

suppose: the hierarchy
$m_1 \ll m_2 \ll m_3$

ν_3

m_t.

ν_2

$m_2 = m_\odot$

$\nu_\odot \Rightarrow \nu_\mu$.

ν_1'

$$\boxed{m \sim \frac{m_D^2}{M_R}}$$

• suppose M_R is the same for all generations

If M_R is the same for all generations

GUT:

$$m_3 = m_2 \cdot \left(\frac{m_t^2}{m_c^2}\right)$$
$$= (2-3) \cdot 10^{-3} \left(1.3 \cdot 10^4\right)$$
$$= (25-40)\, eV$$

Yukawa renorm.

$$\left(\frac{m_t}{m_c}\right)^2 = \left(\frac{180}{1.5}\right)^2 \cdot \frac{1.3}{\cancel{1.44}} 10^4$$

Renorm. between $m_t \to m_G$

SUSY:

20 – 30

$$\rightarrow M_R \sim \frac{(0.5)^2}{2.5 \cdot 10^{-12}} = \frac{0.25}{2.5} 10^{12}$$
$$\sim 10^{11}\ GeV$$

0,5 GeV

2,5

$\Rightarrow$ in the ~~correct~~ cosmologically interesting range of domain HDM

$\Rightarrow$ M_R – is at the intermediate scale

– Axion PQ.
– R.
– [illegible] violation
– radiative generation of

< ~~[illegible]~~

NATURE OF THIS SCALE:

- Peccei-Quinn symmetry
- Horizontal symmetry ?
- SUSY violation scale —— hidden sector? can be related
- Radiatively from GUT-scale (Witten)
- $$M_R = \frac{M_{GUT}^2}{M_{Pl}} \sim 10^{13} \text{ GeV}$$

10^{16} ANOTHER PHENOMENOLOGICAL CONSEQUENCES:

BARION ASYMMETRY:

IN THE DECAYS OF RH NEUTRINOS

$$\nu_R \to l_L + \bar{\Phi}$$
$$\to \bar{l}_L + \Phi$$

asymmetry of this decay

HDM ⟷ SOLAR

CAN RECONCILE.

ATMOSPHERIC ?

How to check?

MIXING:

$$\sin^2 2\theta = 10^{-3} - 10^{-2}$$
$$6 \cdot 10^{-3}$$

can be well described by

$$\boxed{\theta_{e\mu} = \left| \sqrt{\frac{m_e}{m_\mu}} - e^{i\varphi}\theta_\nu \right|} \quad (*)$$

comes from CHARGE LEPTON ~~SECTOR~~ MASS MATRIX.

DIAGONALIZATION OF ν - MASS MATRIX

• STARTED FROM

$\theta_{e\mu} = \sqrt{\frac{m_e}{m_\mu}} \rightarrow$ alone gives $\sin^2 2\theta = 2 \cdot 10^{-2}$

out of best fit

for $\sin^2 2\theta_{e\mu} \gtrsim 5 \cdot 10^{-3}$ eV

THE CONTRIBUTIONS CAN BE OF THE SAME ORDER.

The relation $(*)$ is SIMILAR TO THAT IN QUARK sector

AND follows from Fritzsch ANSATZ for MASS MATRICES:

$$\begin{vmatrix} 0 & m & 0 \\ m & 0 & M' \\ 0 & M' & M \end{vmatrix}$$

14 F4.

How to check this picture:

→ CHORUS, NOMAD

→ $\nu_\mu \to \nu_\tau$ → cover the expected sensitivity region

$\nu_e \to \nu_\tau$

$\sin^2 2\theta \simeq 6 \cdot 10^{-3}$ — from q-sector

will be sensitive to 10^{-4} in the cosmologically interesting domain

$\times$ 0.04
0.0
$4 \cdot 10^{-2}$
$1.6 \cdot 10^{-3}$
$6 \cdot 10^{-3}$

$m(\nu_\tau) \sim 5-30$ eV

→ LONG-BASE-LINE experiments
check "Atmospheric neutrino" region
of parameters

"JUST-SO"
$\Delta m^2 = 10^{-10}$ eV

GRAVITY EFFECT.
~~LARGE~~ MIXINGS

$\nu_\odot \longrightarrow \nu_{Atm}$

$$\boxed{m_\nu \sim m_e.}$$

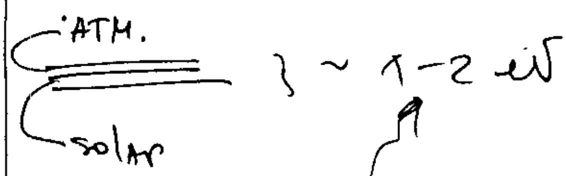
mixing can be enhanced by the see-saw

$$\hat{m} = \hat{m}_D \cdot \underbrace{\hat{M}_R^{-1}}_{\text{Depends on structure}} \cdot \hat{m}_D$$

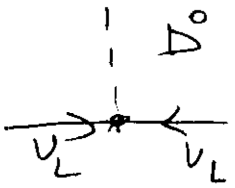
$\boxed{\text{cosmology?}}$

ALL ANOMALIES.

- **STRONGLY DEGENERATE SPECTRUM:**



2β-decay ?

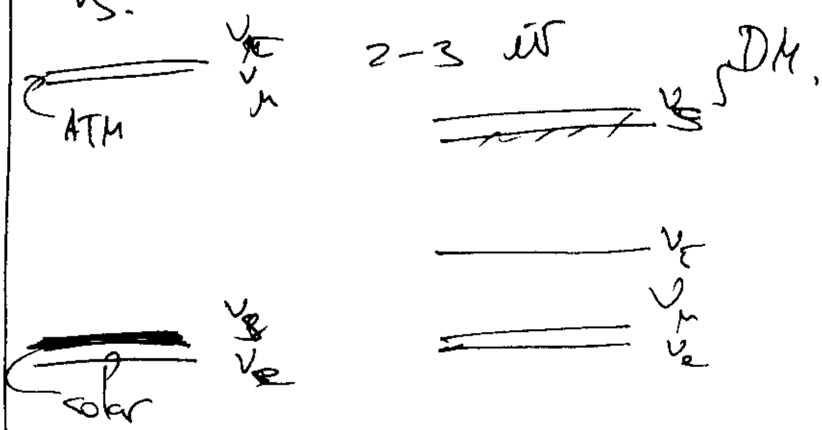


~ HORIZONTAL SU_2 SYMMETRY

- splitting by the see-saw contribution O.K. if what is needed

- **NEW NEUTRINO states**

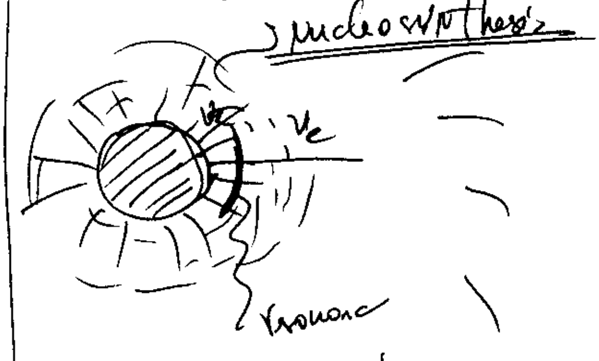
ν_s.



?

SN:

Nucleosynthesis.



$\nu_\tau \to \nu_e$

$\cancel{\nu}$

n — equilibrium.
p

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

$E(\bar{\nu}_e) > E(\nu_e)$ – Neutron Rich medium.

b – DOMINATES

However: if there is a conversion

$E(\nu_e) > E(\bar{\nu}_e)$ $\boxed{\nu_\tau \to \nu_e}$

interchange of spectra

SUMMARY