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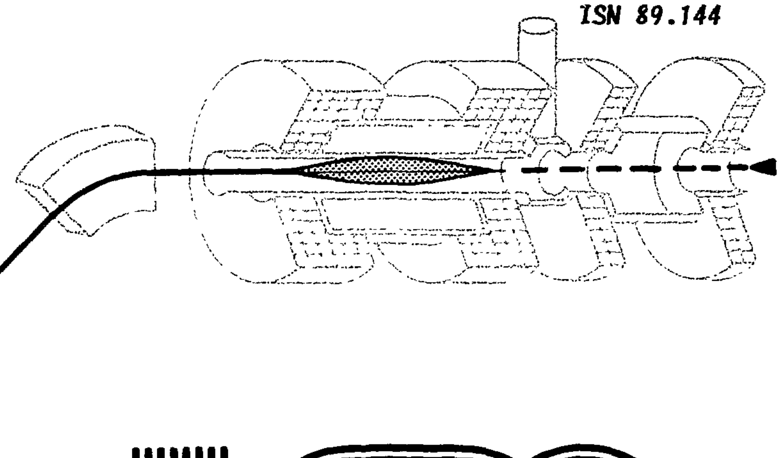

Institut des Sciences Nucléaires de Grenoble

MASS AND OSCILLATIONS OF DIRAC NEUTRINOS

J. Collot

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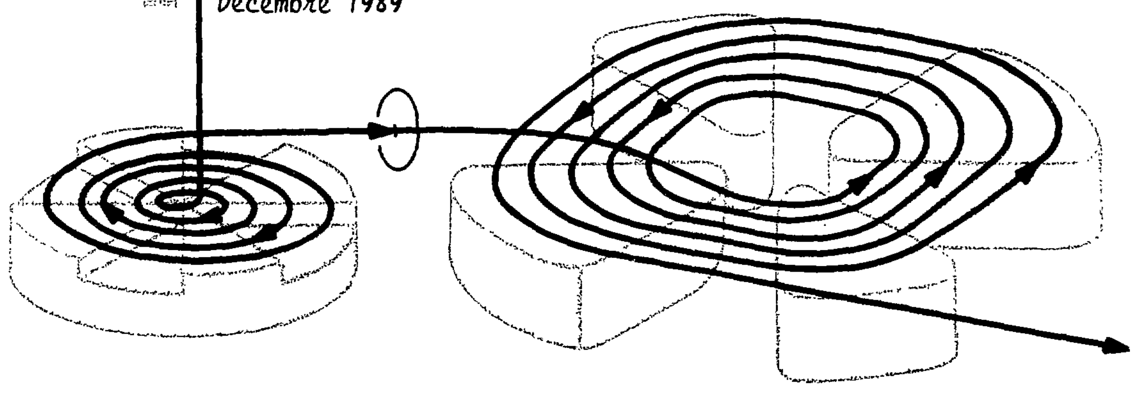

Mass and oscillations of Dirac neutrinos

J. COLLOT [1]

Institut des Sciences Nucléaires de Grenoble, 53 av. des Martyrs,
38026 GRENOBLE FRANCE.

résumé: Dans le modèle le plus simple qu'il soit, nous avons présenté la théorie des neutrinos massifs de Dirac. Une emphase particulière a était placée sur une extension naturelle de la théorie des interactions faibles, qui comporterait une analogie complète entre les quarks et les leptons, conduisant à la prédiction d'oscillations de neutrinos. Les derniers résultats expérimentaux concernant les mesures directes de masses et d'oscillations de neutrinos sont également rappelés.

abstract: In the most economical extension of the standard model, we have presented the theory of massive Dirac neutrinos. We have particularly emphasized that, in this model, a complete analogy between quarks and leptons can be erected and predicts neutrino flavor oscillations. We have reviewed the last experimental results concerning kinetic neutrino mass experiments and neutrino oscillation investigations.

Introduction:

Why should the neutrino which presumedly constitutes the most abundant "matter" particle in the universe be massless? This paradoxical question may be considered as the corner stone of neutrino physics.

Zero has never been accidentally encountered in nature. A well-known illustration of this precept is the zero rest mass of photons (or gluons) that justifies the infinite range of electromagnetic (or color) interaction. No comparable principle or guidance exists for neutrino masses, and consequently it is generally admitted that these physical quantities must not be exactly equal to zero.

We shall show in the first section that, although neutrinos are found massless in the very minimal version of the theory that describes their behavior (GWS theory) , an obvious extension can generate neutrino masses while preserving all the other physical aspects. We shall generalize this mechanism to underline that lepton mixing in weak interaction may exist in analogy to quark mixing. Neutrino oscillations will be finally presented as an observable consequence of this extended model.

We will devote the two subsequent sections to a partial review of experimental results obtained in direct (or kinetic) mass measurements and neutrino oscillation experiments, respectively.

Since Majorana neutrinos were the topic of another talk in this conference, we will restrict ourselves to the simple hypothesis that neutrinos behave as Dirac particles.

I Basic theory of Dirac neutrino mass and oscillations:

The standard theory of massless neutrinos:

The theoretical framework that is of interest when discussing neutrino or, more generally, lepton masses is indeed the well-known GWS model also called $SU(2)_L \otimes U(1)_Y$ theory of electro-weak interactions [1]. The starting point of this theory resides in building a classification of "matter" particles (the ones that

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[1] Member of the BUGEY Collaboration

undergo physical interactions) that sorts right-handed fermions and their associated left-handed ones into singlets and doublets of $SU(2)_L$, respectively:

Leptons	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \; e^-_R$	$\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \; \mu^-_R$	$\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \; \tau^-_R$
Quarks	$\begin{pmatrix}u\\ d\end{pmatrix}_L \; u_R, d_R$	$\begin{pmatrix}c\\ s\end{pmatrix}_L \; c_R, s_R$	$\begin{pmatrix}t\\ b\end{pmatrix}_L \; t_R, b_R$

Because of the pure (V-A) structure of the weak interaction, no place was given to the right-handed neutrinos in the original construction of this theory.

The dynamics of weak interactions is, as in any gauge field theory, engendered by imposing to the free fermionic Lagrangian density, $\mathcal{L}_{free}$, an invariance under the considered group transformations,

$$\mathcal{L}_{free} = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi .$$

After rewritting the mass term in the form of chiral projections:

$$m\bar{\Psi}\Psi = m(\bar{\Psi}_R\Psi_L + \bar{\Psi}_L\Psi_R) ,$$

it manifestly appears that only massless fermions can exhibit the $SU(2)_L \otimes U(1)_Y$ invariance, since ψ_R and ψ_L don't belong to the same group dimensional multiplets. A remedy to this situation consists in introducing a new weak isodoublet of complex scalar fields, namely the Higgs doublet, that couples, for instance,to electronic leptons as follows:

$$\mathcal{L}_{he} = -G_e \left((\bar{\nu}_e, \bar{e})_L \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} e_R + \bar{e}_R (\Phi^-, \Phi^{0*}) \begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \right) .$$

Thanks to its spontaneous symmetry breaking (SSB) potential and a particular choice of the vacuum state, the Higgs isodoublet takes a more simple form when considered as a pertubation around its ground state:

$$\Phi = \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} \Rightarrow \text{SSB} \Rightarrow \Phi' = \sqrt{\frac{1}{2}} \begin{pmatrix}0\\ v + h(x)\end{pmatrix} ,$$

where $h(x)$ is a new scalar particle called the Higgs boson, and v is the Higgs potential vacuum expectation value.

So, when SSB of $SU(2)_L \otimes U(1)_Y$ occurs, $\mathcal{L}_{he}$ transforms into:

$$\mathcal{L}'_{he} = -\frac{G_e}{\sqrt{2}} v(\bar{e}_R e_L + \bar{e}_L e_R) - \frac{G_e}{\sqrt{2}} (\bar{e}_R e_L + \bar{e}_L e_R) h(x) .$$

By identifying the first expression as the mass term of $\mathcal{L}_{free}$, we expressly obtain:

$$\boxed{m_e = \frac{G_e}{\sqrt{2}} v}$$ where: -v= 246 Gev; -G_e is an arbitrary coupling constant.

Indeed, the absence of right-handed neutrinos in the above model prevents us from applying the Higgs mechanism to generate neutrino masses. This is why we commonly say that neutrinos are massless objects in the standard theory.

Dirac mass in the minimal extension of $SU(2)_L \otimes U(1)_Y$:

We schematically showed in the previous paragraph that the massless neutrino prediction is merely derived from the nonexistence of right-handed neutrinos in the standard theory. Therefore, a very modest extension, that consists in adding right-handed neutrinos to the classical theory, is the most economical requisite extension to generate Dirac mass terms. Our former classification in the lepton sector becomes then:

Leptons $\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L$ e^-_R, ν_{eR} $\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L$ $\mu^-_R, \nu_{\mu R}$ $\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$ $\tau^-_R, \nu_{\tau R}$

where: ν_{i_R} $i = e,\mu,\tau$ transform as singlets of weak isospin and hypercharge. This also has the unattractive implication that right-handed neutrinos, a priori, behave as sterile objects for electro-weak interactions.

Neutrino mass generation through the Higgs mechanism develops in a very similar way to the electron case :

$$L_{h\nu_i} = -G_{\nu i}\left((\bar{\nu}_i, \bar{l}_i)_L \begin{pmatrix}-\Phi^{0*}\\ \Phi^-\end{pmatrix} \nu_{iR} + \text{h.c.}\right),$$

where: - $i = e,\mu,\tau$ - $G_{\nu i}$ are arbitrary coupling constants.

After SSB of $SU(2)_L \otimes U(1)_Y$, this Yukawa interaction Lagrangian simply reduces to:

$$L'_{h\nu_i} = -\frac{G_{\nu i}v}{\sqrt{2}}(\bar{\nu}_i\nu_i) - \frac{G_{\nu i}v}{\sqrt{2}}(\bar{\nu}_{iR}\,\nu_{iL} + \bar{\nu}_{iL}\,\nu_{iR})\,h(x),$$

and we can identify the neutrino masses in the terms: $\frac{G_{\nu i}v}{\sqrt{2}}$

$L'_{h\nu_i}$ tells us also that right-handed neutrinos have somehow acquired a more meaningful existence, since they are no longer entirely decoupled from their fermionic partners, but can now interact very weakly by exchanging Higgs bosons. Nonetheless, this theory that only exhibits an "induced" interaction a posteriori, remains conceptually unsatisfactory. In fact, right-handed neutrinos are more natural ingredients of the left-right symmetric model [2] where they fully participate to predominant interactions via weak right-handed currents.

Lepton mixing as an analogy to quark mixing:

A peculiar property of the weak interactions is that they mix the quark mass eigenstates in a way which is extensively described by the famous Kobayashi-Maskawa matrix [3]:

$$\begin{pmatrix}d^w\\ s^w\\ b^w\end{pmatrix} = \begin{pmatrix}U_{ud} & U_{us} & U_{ub}\\ U_{cd} & U_{cs} & U_{cb}\\ U_{td} & U_{ts} & U_{tb}\end{pmatrix}\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$

where d,s,b represent the quark mass eigenstates, and d^w, s^w, b^w their linear superpositions that enter the analytic construction of charged weak currents. An interesting question is to know whether this mixing operation is also at work in the lepton domain. At first sight, considering the empirical rules of lepton number conservation that remain strongly supported by the experimental results [4] , this may look as a useless investigation with a trivial negative answer. It is not quite so immediate if we carefully examine the way quark mixing can be introduced theoretically, and what, in this approach, the implications of lepton mixing would be.

Let us introduce first two generalized Yukawa Higgs-quark coupling Lagrangians in the form:

$$L' = -\sum_{\substack{a=1,2,3\\ q=d,s,b}} \bar{\Psi}_{aL}\, M^{\text{down}}_{aq}\, \Phi\, q^w_R + \text{h.c.}$$

$$L'' = -\sum_{\substack{a=1,2,3\\ q=u,c,t}} \bar{\Psi}_{aL}\, M^{\text{up}}_{aq}\, \tilde{\Phi}\, q^w_R + \text{h.c.}$$

with: $\Psi_{1L} = \begin{pmatrix}u^w\\ d^w\end{pmatrix}$ $\Psi_{2L} = \begin{pmatrix}c^w\\ s^w\end{pmatrix}$ $\Psi_{3L} = \begin{pmatrix}t^w\\ b^w\end{pmatrix}$.

Here Φ, $\tilde{\Phi}(=-i\tau_2\Phi^*)$ represent the classical $SU(2)_L \otimes U(1)_Y$ Higgs-doublets already used above. M^{down} and M^{up} are 3x3 complex matrices of coupling constants.

After SSB, and if we focus our attention only on the mass generating part of these Lagangians, we can rewrite them as:

$$L^{up} = -\frac{v}{\sqrt{2}} \bar{P}_L^w M^{up} P_R^w + h.c.$$

$$L^{down} = -\frac{v}{\sqrt{2}} \bar{N}_L^w M^{down} N_R^w + h.c.$$

$$\text{where:} \qquad P_{L,R}^w = \begin{pmatrix} u^w \\ c^w \\ t^w \end{pmatrix}_{L,R} \qquad N_{L,R}^w = \begin{pmatrix} d^w \\ s^w \\ b^w \end{pmatrix}_{L,R} .$$

Now, if we want to make mass terms explicitly appear in the above expressions, it is necessary that M^{down} and M^{up} be diagonalized. This is achieved with the following relations:

$$M^{up} = U_L\, m^{up}\, U_R^+$$

$$M^{down} = V_L\, m^{down}\, V_R^+$$

m^{up} and m^{down} are then positive real diagonal mass matrices and $U_{L,R}$, $V_{L,R}$ unitary matrices. Under this particular biunitary transformation, $L = L^{up} + L^{down}$ reads:

$$L = -\frac{v}{\sqrt{2}} (\bar{p}_L\, m^{up}\, p_R + \bar{n}_L\, m^{down}\, n_R) + h.c. = -\sum_{q=u,d,\ldots,b} m_q\, \bar{q}\, q$$

$$p = p_L + p_R = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad n = n_L + n_R = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

and

$$p_{L,R} = U_{L,R}^+\, P_{L,R}^w \qquad n_{L,R} = V_{L,R}^+\, N_{L,R}^w$$

where the new eigenstates p,n have definite masses.

Let us now consider the expression of the weak charge raising current:

$$J_\mu^{(+)\ quark} = 2\,\bar{P}_L^w \gamma_\mu N_L^w .$$

If we express this in our new mass eigenstate representation we obtain:

$$J_\mu^{(+)\ quark} = 2\,\bar{p}_L \gamma_\mu U_L^+ V_L\, n_L .$$

in which the product $U^+_L V_L$ forms the Kobayashi-Maskawa matrix:

$$M_{KM} = U_L^+ V_L .$$

Working in the extended $SU(2)_L \otimes U(1)_Y$ model developed before, one can easily perceive that, by analogy, an identical Higgs mixing mechanism can be constructed in the lepton sector. This would yield a new lepton KM matrix linking weak interaction neutrino states to their definite mass eigenstates. This approach was formerly considered by several authors with the purpose of elaborating a theory of weak interactions which would treat quarks and leptons symmetrically [5]. Note that, by convention, we have made the choice here to explicit lepton mixing on neutrinos. In fact, we could have chosen to write this for charged leptons without modifying the final implications.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = M_{KM}^{lepton} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$ with (ν_i, i=1,2,3) being fields of defined masses.

Diagram 1 shows one interesting prediction of this model that explicitly violates the lepton number conservation rules:

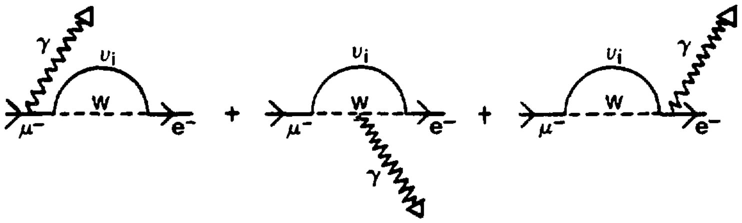

Diagram 1: $\mu^- \to e^-\gamma$

Unfortunately, it can be shown [6] that the branching ratio of such a decay lies many orders of magnitude below the present experimental limits. This point can actually be extended to any rare weak decay and consequently explains why lepton numbers have remained, up to now, good quantum numbers.

Let us turn now to another predicted phenomenon that is more likely to be experimentally observed in the near future. Diagram 2 presents the behavior of free ν_e's if lepton mixing truly occurs in nature.

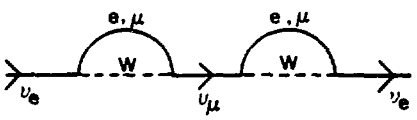

Diagram 2: $\nu_e \rightleftharpoons \nu_\mu$

Here, free neutrinos undergo flavor oscillations that to some extent are comparable to K_0- $\bar{K}_0$ transformations.

In the following, we will assume that we are living in a very simple world composed of only 2 lepton families : (ν_e,e), (ν_μ,μ). A way to partially justify this simplification, is to remark that in the quark KM matrix only the two first generations develop significant mixing amplitudes. Here, M_{KM}^{lepton} takes the reduced form of a rotation matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

A straightforward quantum time evolution calculation leads to the expression of the $\nu_e \to \nu_\mu$ transformation probability for a given distance of flight L:

$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta \ \sin^2(\pi L(m)/L_{osc})} \quad (1)$$

for which $L_{osc}(m) = 2.47\ E_\nu(Mev)/\Delta m^2(ev^2)$ is called the oscillation length,

$$\text{and } \Delta m^2(ev^2) = m_{\nu_2}^2 - m_{\nu_1}^2 .$$

In the present state of our detection technology, neutrino oscillations stand as good candidates to unveal manifestations of a hypothetical lepton mixing scheme.

II Kinetic experiments:

Tritium experiments with magnetic spectrometers:

Acknowleged as the most sensitive and model independent method to determine the rest mass of the electron antineutrino, these experiments have in common the precise measurement of the spectrum endpoint of β-decaying tritium nuclei:

$$^3H \to {}^3H_e + e^- + \bar{\nu}_e \quad (Q=E_0=18.6 \text{ Kev}, \ T_{1/2}=12.3 \text{ y}).$$

If electron antineutrinos are massive particles, the shape of the ^{3}H β-spectrum is given by the classical Fermi theory of allowed transitions kinematically corrected for the $\overline{\nu}_e$ mass:

$$dN(E_e,m_{\nu e}) \propto F(E_e)\, p_e\, (E_e+m_e)\, (E_0-E_e)^2 \sqrt{1-\frac{m_{\nu e}^2}{(E_0-E_e)^2}}\; dE_e$$

where $F(E_e)$ is the relevant Fermi function [7] ; p_e,E_e the momentum and kinetic energy of the electron; $m_{\nu e}$ the assumed electron antineutrino rest mass.

In the presence of massive antineutrinos, the ^{3}H β-endpoint stops $m_{\nu e}$ before E_0($m_{\nu e}$=0) with a rapidly falling behavior.

One of the extreme difficulties inherent to these experiments comes from their low counting rates in the endpoint region. Precisely, the counting time that is required for reaching a mass limit mve , varies roughly as the inverse sixth power of mve. Suppose that a given spectrometer can statistically attain 20 ev in 10 days, the same apparatus will need 2 years to reach 10 ev, irrespective of the other error sources.

The major sources of systematic errors common to all these experiments stem from:

-the knowledge of the spectrometer resolution function,
-the β-particle energy losses in the source itself,
-the detailed calculation of the final state spectrum that influences E_0.

<u>Zürich</u>: The Zürich group [8] used a magnetic spectrometer of the Tretyakov type modified with a radial electrostatic retarding field around the source. Here, the toroidal magnetic field was generated by 36 rectangular current loops arranged in a cylindrically symmetric geometry. The main advantage of this device resided in the fact that the electric and magnetic fields were analytically known, allowing precise Monte Carlo computations of the resolution function. The source consisted of T_2^+ ions implanted into a carbon layer (2000 Å thick) evaporated onto an Al backing. They achieved an energy resolution ΔE=27 ev (FWHM) at a magnetic analysis energy Em=2.2 Kev. Their result is:

$$\boxed{m_{\nu e} < 18\ ev/c^2} \text{ at 95\% CL.}$$

<u>Los Alamos</u>: This group succeeded in building a tritium molecular gaseous source that, in principle, constitutes a great step towards the reduction of the systematic errors due to the electron energy losses inside the source, and the final ^{3}He states known accurately for the T2 molecule. The T2 circulated in a 3.7 m long tube differentially pumped at the extremities. The emitted electrons were guided by an axial magnetic field onto the entrance of a Tretyakov spectrometer. In the last stage of this operation, the β-particles were also accelerated by a 8 Kev high voltage in order to place the magnetic analysis energy well above the tritium decays inside the spectrometer. They measured an energy resolution ΔE=36 ev at 26 Kev and published in 1987 a first result [9] :

$$m_{\nu e} < 27\ ev/c^2 \text{ at 95\% CL.}$$

With an improved version of their set-up (Si detector instead of a proportionnal counter, electric gradient superimposed on the guiding field) they have recently obtained [10] :

$$\boxed{m_{\nu e} < 13.4\ ev/c^2} \text{ at 95\% CL.}$$

<u>ITEP</u>: Employing a tritiated valine source evaporated onto a backing, the ITEP group has been reporting experimental evidences for a non-vanishing $m\nu_e$ since the early eighties [11] . Their last published results [12] obtained in a so-

called model independent technique, i.e. by imposing the mass difference of the neutral atom doublet ^3H-^3He to match the measured values, are:

$$17 ev/c^2 < m_{\nu e} < 40 ev/c^2$$

This allowed mass interval is now totally rejected by the excluding upper limits found by the groups previously quoted.

Tokyo: Concerned about the fact the spectrometer response function and the β-energy losses are the weakest points in the use of solid tritiated sources, this group developed a method to precisely estimate their overall response function by direct experimental procedures [13]. They utilized an organic tritiated salt of natural Cd as a ^3H β-source, and measured their overall response function with a reference source of the same chemical structure but in which ^3H and natural Cd had been replaced by ^1H and radioactive ^{109}Cd, correspondingly. Moreover, their sources were prepared in the form of very thin and uniform film of two molecular layers (total thickness ∝ 50 Å). In the endpoint region, they obtained a global energy resolution $\Delta E = 10$-$16 ev$ depending upon the position of the β-detector in the spectrometer focal plane. Their $m\nu_e$ mass upper limit is:

$$m_{\nu e} < 32 ev/c^2 \quad \text{at } 95\% \text{ CL}$$

Recently, they announced a very preliminary improved limit [14] in which the influence of some systematic errors were not evaluated, yet.

Search for heavy neutrinos in β-spectra:

In this paragraph we will assume again that electron antineutrinos evolve in a mixed lepton world composed of only two fermionic generations.

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

The β-spectrum becomes then:

$$\frac{dN(E_e)}{dE_e} = \frac{dN(E_e, m\nu_1)}{dE_e}\cos^2\theta + \frac{dN(E_e, m\nu_2)}{dE_e}\sin^2\theta,$$

where $m\nu_i$ are the masses of the neutrino eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$.

Consider the case where one of these masses is null; it is straigtforward to show that the *fractional deviation* $\Delta K/K$ *of the Kurie plot from a straight line* takes the approximate expression:

$$\frac{\Delta K}{K} \approx \frac{tg^2\theta}{2}\left(1 - \frac{m\nu_2^2}{(E_0 - E_e)^2}\right), \quad E_e < E_0 - m\nu_2$$

$$\frac{\Delta K}{K} \approx 0, \quad E_e \geq E_0 - m\nu_2$$

The Kurie plot has a "kink" at $E_0 - m\nu_2$ which corresponds to the energy threshold for the production of neutrinos of mass $m\nu_2$. The size of this kink directly determines $\sin^2\theta$.

In 1985, Simpson [15] claimed to have observed evidence of a 17 kev neutrino with a mixing probability satisfying $2\% \leq \sin^2\theta \leq 4\%$. His experiment was based on a *Si(Li) X-ray detector, in which tritium ions were implanted, as a β-calorimeter.* Soon afterwards, a number of authors pointed out that the effective screening potential used in correcting the Fermi function was too large, and that lowering this value would reduce the previous quoted mixing probability [16]. Simpson still argues that his observed "kink" cannot be washed out even in the extreme assumption of a zero effective screening potential [17].

Simpson and Hime have recently redone this experiment in a very similar procedure except that they used a hyperpure Ge X-ray detector [17]. They thoroughly checked every potential instrumental error source they could think of. Nonetheless, their conclusions strengthen the previous claim of a 17 kev neutrino with a somewhat lower mixing probability of .6-1.6%. As a complementary work Simpson and Hime also performed measurements of the ^{35}S β-spectrum with a windowless Si(Li) detector [18]. Here again, they have reported evidence for the emission of heavy neutrinos consistent with those signed in their calorimetric measurements.

It would be unfair not to mention that this 17 kev neutrino has been chased by many other groups in various set-ups without much success [19]; the best upper limit in fact excludes such a heavy neutrino down to a mixing probability <.15% at 90% CL. But, so far, none of these tests were performed with a tritium-doped calorimeter which, in our opinion, represents the cleanest and most sensitive technique to study such an effect.

Accelerator experiments:

ν_μ mass: This experiment [20] was carried out at the SIN high-intensity π^+ facility. It was based on the precise measurement of the μ^+ momemtum (P_u) in the decay $\pi^+ \to \mu^+ \nu_\mu$ at rest. In this special kinetic mode, $m\nu_\mu$ can be related to $m\pi$, $m\mu$, P_μ by the expression:

$$m\nu_\mu^2 = m_\pi^2 + m_\mu^2 - 2m_\pi(m_\mu^2 + P_\mu^2)^{1/2}.$$

The $m\nu_\mu$ mass upper limit derived from this work is:

$$\boxed{m\nu_\mu < 250 \text{ kev}} \text{ at } 90\% \text{ CL}$$

ν_τ mass: This experimental investigation [21] was conducted at the electron-positron storage ring DORIS II at DESY by the ARGUS collaboration. Its principle consisted of measuring the hadronic mass invariant of the 5π system occuring in the tau decay channel $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$. Twelve events were enough to draw the best upper limit recorded so far on $m\nu_\tau$:

$$\boxed{m\nu_\mu < 35 \text{ Mev}} \text{ at } 95\% \text{ CL}$$

III **Experimental status of neutrino oscillations**:

If neutrinos are massive entities, we previously showed that they might as well experience flavor oscillations. From expression (1) that gives the flavor transformation probability, it is not difficult to see that this phenomenon may represent a powerful probe for physics beyond the standard model, even if neutrino masses turn out to be really small ($\propto$ 0.1 ev). On the contrary, kinetic experiments, at least for electron anti-neutrinos, seem to have presently attained their ultimate sensitivity ($\propto$ 10ev). In figure 1, we have roughly sketched the sensitivity regions of the various neutrino oscillation experiments.

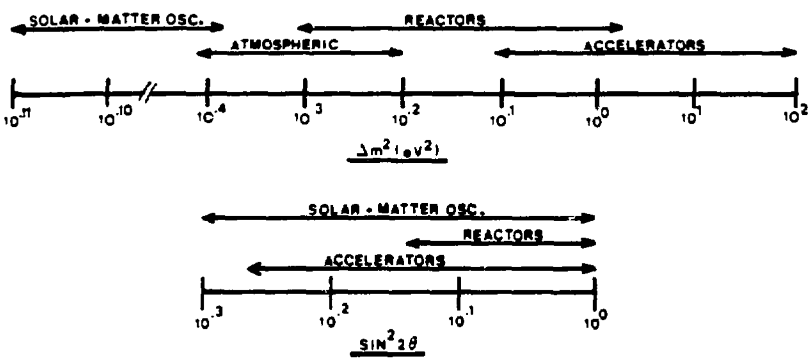

Figure 1: Sensitivities of the various neutrino oscillation experiments

Reactor experiments:

Nuclear power reactors are intense low-energy $\bar{\nu}_e$ sources having strengths up to about $5 \cdot 10^{20}$ s^{-1}. They furnished the first explicit evidence for neutrino induced nuclear reactions [22], and have been utilized for 15 years in neutrino oscillation investigations.

In this context, neutrino oscillations can only be seen in deficit experiments where one compares the observed $\bar{\nu}_e$ rates at a given position from the reactor core to either their predicted values (absolute measurements), or to other measured rates taken at further distances (relative measurements). The latter ones are, in principle, independent of the knowledge of the initial $\bar{\nu}_e$ spectrum but are also insensitive to large values of Δm^2. All of them utilize the same detection reaction which is inverse β-decay: $\bar{\nu}_e + p \rightarrow n + e^+$. Since several good detailed reviews on this topic can be found in the literature [23,24], we will avoid in this paper the lengthy description of the detector working principles. We give in figure 2 the excluded regions for the main experiments. Note that previous claims of positive results [25] have been almost totally retracted [26,27]

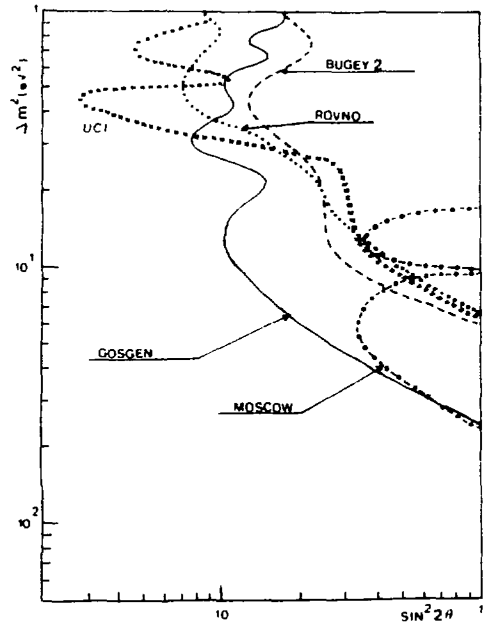

Figure 2: Exclusion plots from reactor experiments.The areas to the right are forbidden. Gösgen 90% CL [28]; Bugey 95% CL [27]; Moscow 95% CL [29]; Rovno 90% CL [30]; UCI 95% CL [31]

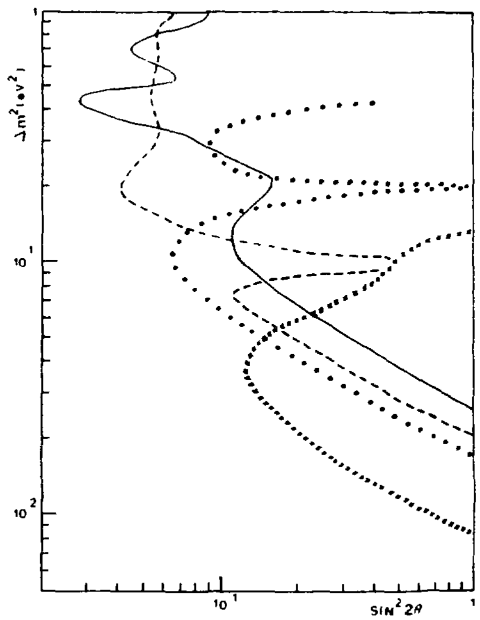

Figure 3: Projected sensitivities of the new Bugey experiment [24]. Two detectors at 16m and 40m, dashed line: relative shapes, dotted line: relative rates. Two detectors at 16m and 120m, x line: relative rates. Full line: envelope curve of the present best limits.

Numerous reactor experiments have been projected for the future, some of which being already officially accepted and under construction.

For instance, the ^{6}Li project of the Bugey group [24,32], which is a multiple detector and reactor experiment making use of a new scintillator [33], will be soon taking data at two positions, simultaneously.

The Rovno group has completed the construction of two new enlarged detectors: a neutrino spectrometer using 1.5 t of Gd-loaded scintillator, and an integral counter consisting of 256 ^{3}He tubes immersed into 1 t of purified water.

A second Russian group is considering the idea of developing a bigger detector based on the ^{3}He integral technique which could be placed at 200 m from a reactor core.

D_2O neutrino integral counters are being devised by both UCI and Moscow. Long distance and very large detector projects are under careful examination by Caltech [34] and IMB.

Such intense activity is likely to start providing, in the next two or three years, much improved constraints on the neutrino oscillation parameters. To illustrate this, we give in figure 3 the projected sensitivity domain of the new Bugey experiment, and in figure 6 what a 1 Kton-at-10 Km detector could, in principle, reach [34] if it were to be constructed.

Accelerator experiments:

At high energy accelerators neutrino beams predominantly exist in the form of ν_μ's produced by in-flight decays of π^+ and K^+ mesons. A supplementary beam stop neutrino facility, at which three neutrino species ($\nu_\mu, \bar{\nu}_\mu, \nu_e$) of equal strengths are available, is also provided at LAMPF.

Many experiments have been conducted at various sites in both the deficit and the appearance modes. The latter mode, where one seeks to observe anomalous neutrino-induced charged-current rates of a flavor initially absent in the beam, is plagued by unavoidable ν_e contaminations of the ν_μ beams, while the former requires high statistics counting to be conclusive.

$\nu_\mu \rightarrow \nu_e$ mode: Figure 4 contains the excluded areas from recent experiments performed in the appearance mode. Clearly, no evidence for neutrino oscillations was recorded.

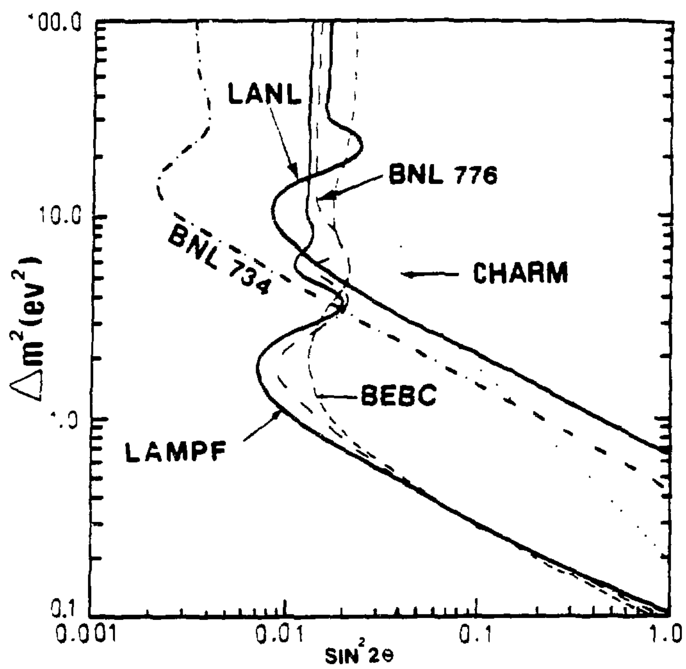

Figure 4: Excluded domains (90%CL) derived from accelerator experiments in the $\nu_\mu \rightarrow \nu_e$ channel. BEBC [35]; BNL734 [36]; BNL776 [37]; CHARM [38]; LAMPF ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) [39]; LANL [40] .The regions to the right are excluded

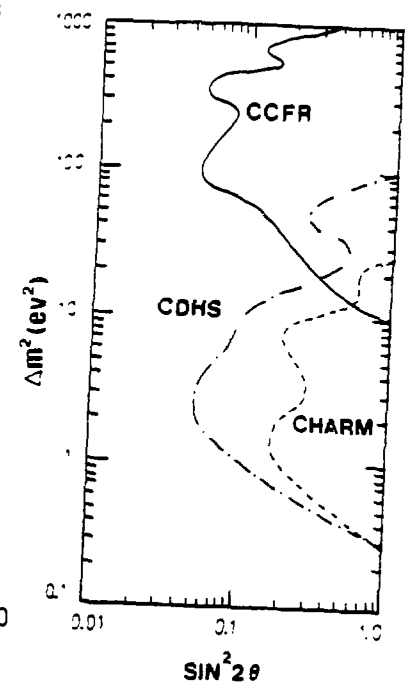

Figure 5: 90% CL upper limit curves from $\nu_\mu \rightarrow X$ accelerator results. CCFR [43]; CDHS [44] ; CHARM [38]. The regions to the right are excluded.

Results from experiment PS191 [41] gave, a few years ago, an indication for an anomalous electron production induced in the CERN PS neutrino beam. In spite of a recent confirmation at BNL [42] with the same statistical significance, the authors have prudentially avoided interpreting this electron excess in mere terms of neutrino oscillations, but instead mention a possible underestimation of the ν_e contamination of the beam.

$\nu_\mu \rightarrow X$ mode: Here, one commonly looks for differences in the ν_μ induced rates normalized by the initial flux in two detectors at different distances from the neutrino production location. We have presented in figure 5 results of three groups consistent with unity excluding then neutrino oscillations within their sensitivities.

Solar neutrinos:

The solar neutrino question has received, in recent years, further stimulation from both new theoretical developments in neutrino oscillations through matter [45] and the last observed ν_e rates of Kamiokande [46] that seem to confirm the ^{37}Cl experiment of DAVIS et al. [47].

In the future, SAGE [48] and GALLEX [49] will provide complementary information relying less on the Sun Standard Model (SSM) input ingredients. SNO [50] will certainly join the increasing number of neutrino observatories.

Depicted in figure 6 are the allowed domains, in case the MSW effect takes place, for the ^{37}Cl experiment if the ^{8}B solar neutrino rates are confirmed at 3/4 or 1/2 of the SSM expectations.

Conclusion:

Neither the kinetic experiments nor the oscillation searches have demonstrated yet that neutrinos really behave as our theoretical assumptions suggest they could.

Exotic results, experimental puzzles, and indications may be found in the literature, but it is extremely unpleasant that they do not help to form a coherent view of these particles. Is this not a proof that searches for the true nature of neutrinos have to be prolongued and perhaps somewhere else?

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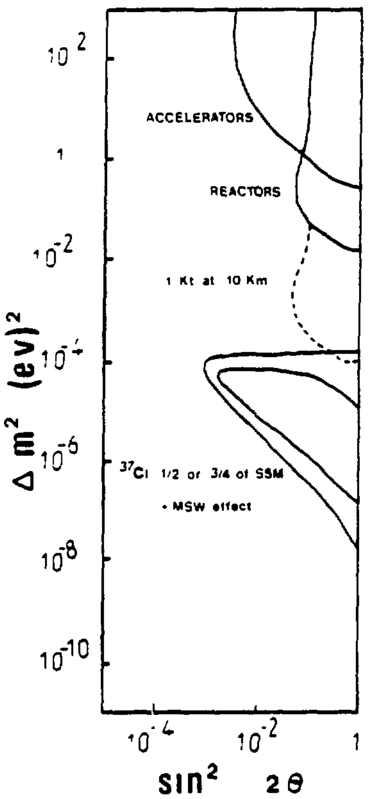

Figure 6: World best 90% CL upper bound curves from accelerators and reactors. Expected sensitivity domains for a large detector by a reactor [34] and ^{37}Cl experiment if due to osc. in matter.

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