EXPERIMENTS ON LEPTON AND BARYON STABILITY AND OSCILLATION PHENOMENA

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ABSTRACT

The various experiments on lepton number conservation and on nucleon stability presently being carried out or prepared will be reviewed, and their relative merits compared and discussed. The first part of the paper will be devoted to the measurement of the ν mass and to the present limits on the conservation of the total lepton number and of the various lepton flavours. The existing results and future projects on the strictly connected problems of neutrino oscillations at nuclear reactors, pion factories and high energy accelerators will be also discussed, together with oscillations of solar and atmospheric ν . The second part of the paper will concern the few results and the many planned detectors on nucleon decay with particular emphasis to the problem of background and of the various experimental approaches. Oscillation experiments on neutron-antineutron oscillations at nuclear reactors will be also considered.

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1. INTRODUCTION

Lepton and baryon numbers were never considered as sacred by experimentalists, and searches to reveal their violation have been carried out since almost fifty years (Weinberg 1981a and 1981b). Their non-conservation has been, on the other hand, suggested on cosmological or astrophysical basis, for instance to explain the baryon and antibaryon asymmetry of the Universe (Sakharov 1967, Steigman 1981), or the failure to detect a sufficient rate of events produced by solar ν (Gribov and Pontecorvo 1969). In these last years, however, a much larger experimental effort on these subjects have been stimulated by modern gauge theories which, even without grand unification (Weinberg 1980), imply lepton and baryon number violation. These theories have been reviewed recently by many authors (Goldmann and Ross 1979, Machacek 1979, Gaillard 1979, Wilczek 1979, Weinberg 1979, Weinberg 1980, Langaker 1980, Nanopoulos 1980, Pati 1980, Ellis 1980, Giorgi and Glashow 1981, Primakoff and Rosen 1981, Glashow 1981) and discussed in this meeting (Ellis 1981, Salam 1981). I will not be concerned here with them, or with their cosmological implications (Sawada and Sugamoto 1979) which have been reviewed here by G. Steigmann (1981).

Let me only to point out, as an experimentalist, that lepton and baryon stability should be searched with open mind. It is therefore fortunate that present experiments aim to detect a variety of violations: not only of the total lepton number L , but also of the individual lepton flavours (L_e, L_μ, L_τ); not only of the total baryon number B , but also of various combinations of B and L . They will therefore not only hopefully test the validity of gauge theories, but also allow to chose among the different models.

All these experiments are very challenging, and often on the borderline of technical feasibility. They are in general based on the detection of very rare or unusual events or processes, and have almost always to deal with severe background problems. Surprisingly enough, they only rarely require what has been the most obvious tool of elementary particle physics: accelerators of very high energy.

I will review here separately experiments on neutrino mass, lepton and flavour stability, baryon stability and nucleon-antinucleon oscillations.

2. NEUTRINO MASS

The possibility of a non-zero neutrino mass is obviously strictly connected to lepton non-conservation and neutrino oscillations. The mass of muon and tau neutrino is still poorly known, with upper limits of 0.57 MeV (Daum et al., 1978) and 250 MeV (Bacino et al., 1979), respectively. The mass of electron neutrino and antineutrino can be obtained by carefully determining the high energy tail of the electron spectrum in beta decay. The sensitivity of the experiment is obviously greater when the transition energy is low. Unfortunately, for the best positron decay, namely

the transition energy is considerable (545.7 keV), and the present 68% c.l. upper limit for electron neutrino mass is only of 4100 eV (Beck and Daniel 1968).

Measurements of the electron antineutrino mass are based on the more favourable decay

with a transition energy which has been recently evaluated to be (18.567 ± 0.005) keV (Simpson 1981). Tritium experiments have been so far mostly performed by measuring the electron spectrum by means of a magnetic spectrometer, and by comparing the high energy tail of the experimental spectrum with the shape predicted theoretically for a zero neutrino mass. Up to last summer all experimental results agreed with a zero mass with upper limits around 50 eV (Simpson 1981). The common believe that this limit, of the order of atomic energies, could hardly be improved, was contradicted by the result of an experiment carried out for more than five years by the Moscow group (Lyubnimov et al., 1980 and 1981). Electrons from a $2 \mu\text{g}/\text{cm}^{-2}$ of valine ($\text{C}_5\text{H}_{11}\text{NO}_2$), containing 18% of tritium, were magnetically examined with a rotation angle of 720° . The end spectrum is clearly inconsistent with zero neutrino mass (fig. 1) and indicate an electron antineutrino mass between 14 and 46 eV, at the 99% confidence level. The authors themselves suggest some effects which could have simulated a non-zero neutrino mass, while others have been pointed out by K.E. Berkvist (1980), like the not completely correct use of the resolution function in the electron energy, the complexity of the valine

molecule, possible systematic errors in the parametrization of the electron spectrum etc. There is, however, no obvious effect which could have simulated the result, and to disprove it one has to reach a sensitivity of at least 10 eV, with considerable improvements in the present techniques. It is also essential to check the result with an experimental approach different from the magnetic spectrometry. One (Simpson 1981) consists in the high energy implantation of tritium nuclei into a Si(Li) detector to measure directly the β spectrum. Another approach, suggested by A. de Rujula (Andersen et al. 1981) is based on the electron capture process

$$\bar{\nu}_e + (A, Z) \rightarrow (A, Z + 1) + \nu_e + h\nu \quad (3)$$

which occurs in $\sim 10^{-4}$ of all electron captures. The γ photon spectrum, which has obviously a tangent at the end equal to zero for a massless neutrino, provides a sensitive determination of the neutrino mass which, unlike electron spectra, is independent on atomic or molecular effects. Nuclei like ^{157}Tb , ^{163}Ho and ^{193}Pt , which are of considerable interest for low transition energy and shape of the photon spectrum in the high energy region, are going to be produced, in view of this experiment, by the Isolde facility at CERN.

The relevance of a non-zero neutrino mass in the frame of grand unified theories and of cosmology has been emphasized recently (Senjanovic 1981a and 1981b, Mahopatra and Sejanovic 1981, Steigman 1981, Ellis 1981) and in the reviews quoted in the introduction. It will therefore not be discussed here.

3. LEPTON NUMBER CONSERVATION

In the standard theory of weak interactions leptons of different flavour are grouped as follows:

$$(\nu_e, e^-, \bar{\nu}_e, e^+); (\nu_\mu, \mu^-, \bar{\nu}_\mu, \mu^+); (\nu_\tau, \tau^-, \bar{\nu}_\tau, \tau^+) . \quad (4)$$

Let us first consider the possibility that total lepton number is conserved, but that individual flavours are not. The separate conservation of electron and muon number has been investigated at accelerators of the "pion factory" type, where very intense beams of low energy pions and muons can be produced. No evidence for any violation of flavour has been found

with impressive limits (Boehm 1980, Shenker 1981) on the branching ratios, which I report here at the 90% confidence level

$$\mu^+ \rightarrow e^+ + \gamma \leq 2 \times 10^{-10} \quad (\text{Bowman et al. 1978}) \quad (5)$$

$$\mu^- \rightarrow e^+ + e^- + e^+ \leq 1.2 \times 10^{-9} \quad (\text{Korenchenko et al. 1976}) \quad (6)$$

$$\frac{\mu^- + {}^{32}\text{S} \rightarrow e^- + {}^{32}\text{S}}{\mu^- \text{ capture}} \leq 7 \times 10^{-11} \quad (\text{Badertscher et al. 1978, Boehm 1980}) \quad (7)$$

Another interesting limit has been obtained on the reaction

$$\frac{\mu^- + {}^{32}\text{S} \rightarrow e^+ + {}^{32}\text{Si}}{\mu^- \text{ capture}} < 9 \times 10^{-10}, \quad (\text{Badertscher et al. 1978, Boehm 1980}) \quad (8)$$

which would imply either violation of total lepton number, or a different regrouping of the lepton in the various flavours.

An interesting limit on a similar process has been obtained recently with the reaction

$$\frac{\mu^- + {}^{127}\text{I} \rightarrow e^+ + {}^{127}\text{Sb}}{\mu^- \text{ capture}} < 3 \times 10^{-10}, \quad (\text{Abela et al., 1980}) \quad (10)$$

by searching for ${}^{127}\text{Sb}$ with radiotechnical techniques.

The sensitivity on experiments on reactions (5) and (10) is going to be improved by two orders of magnitude in the near future at Los Alamos and SIN, respectively.

Experiments have also been carried out on the validity of the multiplicative law, which would imply separate violation of electron and muon number, while their product would be conserved. This allows reactions forbidden by the additive law like

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu \quad (11)$$

$$\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e, \quad (12)$$

which have been investigated recently at Los Alamos (Willis et al. 1980) and at CERN (CHARM 1980), respectively, with the following results:

$$\frac{\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu}{\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu} < 0.065 \text{ (90\% CL) ,} \quad (13)$$

$$\frac{\bar{\nu}_\mu e^- \rightarrow \mu^- \nu_e}{\nu_\mu e^- \rightarrow \mu^- \bar{\nu}_e} < 0.09 \text{ (90\% CL) .} \quad (14)$$

The "classical" way to search for violation of the total lepton number is the process of double beta decay, which has been proposed by M. Goeppert-Mayer (1935), immediately after the Fermi theory of weak interactions. Let us suppose that a nucleus (A,Z) be stable for single beta decay to (A,Z+1) due to energy conservation or because this process is strongly hindered by large changes in the spin-parity state. Double beta decay can then occur in principle in two channels

$$(A,Z) \rightarrow (A,Z+2) + 2 e^- + 2 \bar{\nu}_e , \quad (15)$$

$$(A,Z) \rightarrow (A,Z+2) + 2 e^- . \quad (16)$$

This latter process, which obviously implies lepton non-conservation, and therefore Majorana neutrinos, would be strongly enhanced, with respect to the former one, by the much larger available phase space.

I will not enter here into a detailed description of the various experiments which have been carried out so far (Fiorini 1977, Wu 1981) or on the various theories which have been constructed in the "pre-gaugean" (Bryman and Picciotto 1978) or "gaugean" heras (Vergados 1980, Primakoff and Rosen 1981). I would only like to add a few comments on this very interesting topic.

A first concerns the experimental approach, which can be either of the "geological" or of the "direct" type. The former consists in the radiochemical investigation of a rock containing the (A,Z) nucleus for "abnormal" isotopic abundance of the "granddaughter" nucleus (A,Z+2). This method is very powerful and it has allowed to obtain the only unambiguous evidence for double beta decay (for ^{82}Se , ^{128}Te and ^{130}Te). It is however impossible to discriminate directly with geological methods between two-neutrino and neutrinoless decays, and hard to exclude that the abnormal abundance of the granddaughter nucleus could have been produced by

processes other than double beta decay, like interactions of cosmic rays, of solar neutrinos etc. Conversely, part of the granddaughter nucleus, always a gas, could have escaped during hydrothermal alterations of the rock. For this reason the most interesting of these results is, in my opinion, the one obtained with the contemporary measurement of the isotopic abundance of ^{128}Xe and ^{130}Xe produced by double beta decay of the corresponding isotopes of tellurium (Hennecke 1978). Since the transition energies, for double beta decay of ^{128}Te and ^{130}Te are very different, and since therefore the theoretically determined rates depend strongly very dependent on the two-neutrino and neutrinoless hypothesis, the experimental ratio

$$\frac{(\text{Te-128})}{(\text{Te-130})} = (1.57 \pm 0.10) \times 10^3 \quad (17)$$

can be usefully compared with theory.

Unambiguous evidence for neutrinoless double beta decay could however be obtained in experiments based on "direct" measurements (with scintillators, solid state detectors, discharge and cloud chambers etc.), where the sum of the two electron energies can be measured in order to search for the peak expected when no neutrino is emitted. No experiment has shown so far evidence for any type of double beta decay (Fiorini 1979a, Boehm 1980, Wu 1981), with exception of the cloud chamber experiment by the Irvine group (Moe and Löwenthal 1980), where twenty candidates for two neutrino double beta decay of ^{82}Se have been detected. The authors cannot, however, exclude that this sample could be due to radioactive background. Moreover, the obtained rate for double beta decay would be more than an order of magnitude larger than that found with geological methods.

A second remark concerns the way double beta decay is evaluated theoretically. This process, in the neutrinoless channel, has been taken by B. Pontecorvo (1968) as a direct first order transition with $\Delta L = 2$ and $\Delta S = 0$. Most of the gaugean and pre-gaugean theories, however, treat double beta decay as a second order sequence of two single beta decays. Neutrinoless double beta decay is then mediated by a virtual neutrino emitted by a nucleon and absorbed by another one in the same nucleus. The rate is calculated by closure, and found to be proportional to the square of the inverse of the average distance between the two nucleons, which is

roughly taken as equal to the nuclear radius. It has however been suggested (Primakoff and Rosen 1972, Halprin et al. 1976) that the virtual neutrino can be exchanged between two quarks of a resonance present in the nucleus, leading to decays like

$$n \rightarrow e^- + e^- + \Delta^{++} \quad (18)$$

$$\Delta^- \rightarrow p + e^- + e^- \quad (19)$$

The rate would then be proportional to the inverse of the square of the radius of the nucleon, and therefore more than an order of magnitude larger than in the "two-nucleon" mechanism. One has however to point out that resonances have been proved to be present in the nucleus only in proportion of a few percents. The resonance contribution seems therefore not large, and sometimes even negligible, at least in the two neutrino channel (Doi et al. 1981a and 1981b). It has probably been considered as important by Primakoff and Rosen because these authors have taken average squares of the nuclear matrix elements for the two nucleon mechanism, which are in general too small (by an order of magnitude). One has to note incidentally that nuclear matrix elements have been calculated in detail only in a few cases (Fiorini 1977, Vergados 1976, Haxton et al. 1980 and 1981).

A third remark refers to the possibility to investigate double beta decay to an excited state of the $(A, Z+2)$ nucleus. Up to one year ago all calculations on double beta decays have been carried out for the $0^+ \rightarrow 0^+$ transition between the ground states of the (A, Z) and $(A, Z+2)$ nuclei, with the only commendable exception of the work by Molina and Pascual (Molina and Pascual 1977). Only recently P. Rosen (1981) and M. Doi et al. (1981a and 1981b) have considered in the gaugean theories transitions from the 0^+ ground state of the parent nucleus to excited states of the grand-daughter one (the first excited level is always a 2^+). The "minimal" conditions for existence of neutrinoless double beta decay are either a massive neutrino with the normal left-handed currents, or a zero mass neutrino with a small admixture of right-handed components. Neutrinoless decay to the 2^+ state can occur only via the latter channel, and can therefore be used to discriminate between the different models of lepton number non-conservation, as it will be considered later. Double beta decay to an excited nuclear level, which then decays with emission of a gamma ray, is

experimentally appealing. It has, however, been investigated up to now only by the Milano group, which have set an upper limit of 3×10^{21} years (at 68% CL) for neutrinoless double beta decay of ^{76}Ge to the 2^+ excited state of ^{76}Se at 559 keV (Fiorini 1977). Various experiments on double beta decay to excited nuclear levels have been suggested (Fiorini 1978), and one of them, on the decay of ^{150}Nd on the 2^+ excited state of ^{150}Sm at 334 keV, is presently being carried out with a Ge(Li) set-up installed in a laboratory in the Mont-Blanc tunnel (fig. 2). There is up to now no evidence for two neutrino or neutrinoless double beta decay to this excited level, with a lower limit on the half lifetime of 2×10^{18} years, at 68% confidence level.

The last remark concerns the comparison between experimental results and theoretical predictions. In the "pre-gaugean" era the neutrino mass was taken as zero and the negative results of direct experiments, as well as the positive results of geological experiments (totally attributed to the two-neutrino channel) were used to obtain limits on the lepton non conserving parameter. Limits of 10^{-3} to 10^{-4} , strongly dependent on the nuclear matrix elements, were found in this way.

The most detailed predictions based on gauge theories have been recently given by M. Doi et al. (1981a and 1981b), who have taken into account the two nucleon and resonance mechanisms for decay both to the ground and to various excited states. They have found that two neutrino double beta decay occurs in general mainly via the two-nucleon mechanism and via the 0^+-0^+ transition. The left-handed current massive neutrino contribution to the neutrinoless channels occurs, mainly via the two nucleon mechanism, in the 0^+-0^- transition, since decays to excited levels are forbidden. On the contrary, the zero mass right-handed current contribution is considerably affected by the 0^+-2^+ channel and by the resonance contributions. Since their theoretical predictions for two the neutrino decay seem inconsistent with the experimental ratio between lifetimes of ^{128}Te and ^{130}Te , reported in reaction (17), M. Doi et al. assume this experimental results as positive evidence for lepton number non-conservation. In absence of right-handed current this leads to positive evidence for a massive neutrino with $m_\nu \sim 35$ eV.

This result is very interesting, but has to be taken with some care. Detailed calculations of the half lifes for ^{128}Te and ^{130}Te by Haxton

et al. (1980) give values considerably larger than the geological ones, but their ratio, in the two neutrino hypothesis, are consistent with the experimental value of reaction (17). Moreover, the same authors (Haxton et al., 1981) as well as P. Rosen (1981) use the experimental limits for 0^+-0^+ decay of ^{82}Se and 0^+-0^+ and 0^+-2^+ decays of ^{76}Ge to obtain limits on the mass of the neutrino in absence of a right-handed current contribution. Comparison with the experimental data on selenium and germanium yields upper limits for the neutrino mass of 12 and 15 eV, respectively.

4. NEUTRINO OSCILLATIONS

If lepton flavours are not separately conserved and if at least one of the neutrino masses is different from zero, oscillations among electron, muon and tau neutrinos should occur (Pontecorvo 1958, Belenki and Pontecorvo 1978, Boehm 1980, Rosen and Kayser 1981, Barger et al. 1980, Barger 1981). Oscillations between electron-muon, electron-tau and muon-tau neutrinos are not necessarily equivalent, and the existence of one or another can be used to discriminate among different models (Bilenki and Pontecorvo 1981). If we limit ourselves to oscillations between two neutrino flavours only, for instance electronic and muonic, the corresponding fields can be considered as combinations of two Majorana neutrinos with finite masses m_1 and m_2 , respectively

$$\nu_e = \nu_1 \cos\alpha + \nu_2 \sin\alpha \quad (20)$$

$$\nu_\mu = -\nu_1 \sin\alpha + \nu_2 \cos\alpha \quad (21)$$

where α is the mixing angle. An initially pure electron neutrino (anti-neutrino) beam would then contain at a distance D from its origin a muon neutrino (antineutrino) impurity of relative intensity

$$P[\nu_\mu(\bar{\nu}_\mu)] = \frac{I(\bar{\nu}_\mu)}{I(\bar{\nu}_e)} = 0.5 \sin^2 2\alpha \left(1 - \cos \frac{2.534 \Delta D}{E_\nu}\right), \quad (22)$$

where D is in metres, E in MeV and $\Delta = |m_1^2 - m_2^2|$ in eV^2 . One should note that the Majorana total lepton number violating description would lead also to particle-antiparticle oscillations.

Oscillations experiments search either for a loss of neutrinos of the "right" flavour, or for the appearance of neutrinos of the "wrong" one. The sensitivity of the experiment is given by two parameters:

- (a) the precision with which the impurity P can be determined;
- (b) the experimental factor D/E , namely the ratio between the distance of the source and the neutrino energy.

The experimental result can be interpreted in two extreme hypotheses:

- (a) Large Δ values. The cosinus value is averaged to zero and P gives a value of the mixing angle.
- (b) Low Δ values. A non-zero value, or a limit on P , would involve both Δ and mixing angle.

Neutrino oscillations can, and have been, studied with at least five different experimental approaches.

4.1 Solar neutrinos

The sun represent a very intense source of electron neutrinos and a series of experiments by F. Davis et al., based on the reaction

indicates an interaction rate, and therefore a neutrino flux, well below the theoretical estimates. The present experimental value (Cleveland et al. 1980) for capture rate is (2.1 ± 0.3) SNU, where one NSU corresponds to 10^{-36} neutrino captures per target nucleon per second, while the most recent theoretical predictions are larger by a factor 3 to 4 (Bahcall 1980). This discrepancy cannot yet be taken, at least in my opinion, as evidence for neutrino oscillations among the various neutrino flavours, since theoretical predictions are strongly model dependent. Moreover, reaction (23) is only sensitive to the high energy part of the solar neutrino spectrum. To reach a firm conclusion, one has to wait the new experiments on different neutrino targets, like those on the reaction

where the sensitivity to lower energies allows to cover a much larger fraction of the solar neutrino spectrum.

By considering the two "sensitivity parameters" defined in the preceding page, one notes that, while the average ratio D/E is very large ($\sim 10^{11}$ m/MeV) in solar neutrino experiments, parameter P is badly determined, due to our poor knowledge of the neutrino flux.

4.2 Neutrinos from power reactors

Power reactors provide very intense beams of electron antineutrinos, which are produced at a rate of about five per nuclear fission. Theoretical calculations of the energy spectra are very difficult, since a large fraction of the decay schemes of fission products is unknown. Moreover, contributions by ^{235}U , ^{238}U and ^{239}Pu are considerably different (fig. .

Up to one year ago all results on low energy neutrinos were obtained in experiments at the Savannah River Plant, a military reactor of 1.8 GW total power with a flux of 2×10^{13} antineutrino-electrons $\text{cm}^{-2} \text{s}^{-1}$ at 11 m distance from the centre of the core. A process which can be used to investigate neutrino oscillations is

$$\bar{\nu}_e + p \rightarrow e^+ + n, \quad (25)$$

where the e^+ was detected via its two annihilation gamma rays, and n by a suitable doping of the hydrogen rich scintillator which acts also as neutrino target. A possible lack of events in previous experiments (Sobel 1980) at 6.5 and 11.2 m from the reactor core were not used to study neutrino oscillations, mainly due to uncertainties on the neutrino flux.

More recently an experiment was carried out at 11.2 m (Reines et al. 1980) on the charged and neutral current reactions

$$\bar{\nu}_e + d \rightarrow e^+ + n + n, \quad (26)$$

$$\bar{\nu}_e + d \rightarrow \nu_e + p + n. \quad (27)$$

The ratio between these two processes is rather independent on the neutrino flux while strongly depending on the $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ oscillations, which would suppress the charged current component leaving practically unaffected the neutral current one. The experimental value of the ratio between the two reactions, obviously corrected for detection efficiency and background, was

found to be definitely lower (by 3 and 2.7 standard deviations) than the one predicted theoretically on the basis of the neutrino spectra calculated by Avignone and Davis and Vogel, respectively. This result stimulated various theoretical discussions (Raychauduri 1980a and 1980b, Silverman and Soni 1980) and also critical remarks (Feynman and Vogel 1980, Dar 1980). Considerable attention was therefore focused on a new experiment carried out by the CIT-Grenoble-München Collaboration at the ILL reactor in Grenoble, where the neutrino intensity is lower ($9.8 \times 10^{11} \nu_e \text{ cm}^{-2} \text{ s}^{-1}$ at 8.76 m from the centre of the core), but where one can profit of the typical advantages of an experimental reactor (a very small core, fuel made only by ^{235}U , better shielding etc.). The experiment was carried out on the inverse beta decay reaction (25) with a detector made by 30 slabs of hydrogen rich scintillator to detect the gamma rays from positron annihilation, interleaved with ^3He chambers to detect the neutron (fig. 4).

The obtained spectrum is in good agreement with theoretical predictions in absence of oscillations (Boehm et al. 1980, Kwon et al. 1981) at least for the neutrino energy distribution obtained by Davis and Vogel. One has, moreover, to point out that the same collaboration has measured experimentally (Schreckenbach et al. 1981) the beta spectrum from a ^{235}U target exposed to a thermal neutron beam at the same reactor, finding a result in good agreement with the prediction for this spectrum by Davis and Vogel. The comparison between the two experimental results is shown in fig. 5.

I would like to conclude that, if one takes into account the still existing uncertainties in the evaluation of the flux, the obvious experimental difficulties connected with the low rate of events and the large background, and the low and not well-known detection efficiency, there is at present no real disagreement between these two results, and at least at the moment, no real evidence for neutrino oscillations. It is indeed fortunate that two new experiments are planned at the Savannah River Plant, one at a fixed distance of 15.5 m and another at a distance variable between 12 and 35 m (Sobel et al. 1980) and that a new search at two different positions is going to be carried out by the CIT-München Collaboration at the 2.7 GW reactor.

4.3 Oscillation experiments at pion factories

Experiments at pion factories exploit the very intense beams of low energy pions produced by dumping proton beams on thick and dense targets (fig. 6). Since the π^- are absorbed, the following decays occur, if the additive law is valid:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad (28)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu. \quad (29)$$

The only experiment on oscillations carried out so far is the one by P. Nemethy et al., (Nemethy et al., 1981) at LAMPF, with a 6 m³ Cerenkov detector, shielded with drift chambers against cosmic radiation (fig. 7).

Two reactions have been studied to reveal either a lack of electron neutrinos, or the presence of electron antineutrinos, which would both imply electron neutrino oscillations. By filling the detector with D₂O the ratio

$$R' = \frac{\nu_e}{\nu_\mu} = 1.09 \pm \begin{matrix} 0.37 \\ 0.41 \end{matrix} \quad (30)$$

was found for the reaction

$$\nu_e + d \rightarrow e^- + p + p \quad (31)$$

while, by filling with water, a ratio

$$R = 0.001 \pm 0.061 \quad (32)$$

was found for the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (33)$$

The errors in reactions (30) and (32) include statistics and systematics. The dramatic change of counting rates when the D₂O filling is changed with water can be seen in fig. 8(a) and (b).

The 90% CL limits on oscillation are, for maximum mixing, $\Delta \lesssim 1.75 \text{ eV}^2$ and $\Delta \lesssim 0.91 \text{ eV}^2$, from reactions (30) and (32), respectively.

Various new experiments are at present being considered at LAMPF to search for neutrino oscillations. Some of them are of the "beam dump" type (Romanoski et al. 1980, Duon-Van and Phyllips 1980); others are based on the use of a "focused" neutrino beam, with a larger average energy (~ 150 MeV) (Bowles et al. 1981, Ling et al. 1981, Mann 1981). The construction of a 150 m long, 5 m wide underground tunnel where the detector could be moved (Duon-Van and Phyllips 1980), and even a possible experiment with nuclear bombs (Kruse et al. 1980) have been considered.

4.4 Experiments at high energy accelerators

Various limits on oscillations have been obtained at high energy accelerators in "non-dedicated" neutrino experiments. The first results were obtained with the bubble chamber Gargamelle at the CERN PS (Bellotti et al. 1976, Blietschau et al. 1978). They take advantage of the fact that focused muon neutrino beams contain only a small fraction of electron neutrinos (from a fraction of percent around one GeV to a few percents at tens of GeV). If neutrino oscillations of the type $\nu_\mu \rightleftharpoons \nu_e$ occur, an excess of electron neutrino events would appear in the detector, and the parameter P defined in reaction (22) can be determined with good precision. The results by the Gargamelle collaboration (fig. 9) show that, for maximal mixing parameter, Δ is lower than 1 eV^2 .

Similar limits on $\nu_\mu \rightleftharpoons \nu_e$ oscillations have been obtained in more recent bubble chamber (Cnops et al. 1978, Armenise et al. 1981a and 1981b) and counter (Mann 1981) experiments. Oscillations among different neutrino flavours have also been investigated. In particular, bubble chamber experiments at CERN (Armenise et al., 1981(a) and 1981(b)) have searched for $\nu_\mu \rightleftharpoons \nu_\tau$ oscillations, where the ν_τ neutrino interacts in the chamber, producing a τ lepton which is known to decay with a branching ratio of 20% into an electron, simulating an electron neutrino event. Limits of 6 eV^2 , 3 eV^2 and 3.2 eV^2 have been obtained, respectively, for maximum mixing. An alternative approach to obtain the same limit has been taken by T. Kondo et al. (1981) by searching directly for τ 's produced by a high energy neutrino beam in a nuclear emulsion, where the short decay lengths of these leptons can be observed, and eventually measured. A limit

of $\Delta \leq 3.5 \text{ eV}^2$ at 90% CL has been obtained. Other experiments are of the "missing neutrino" type, namely on $\nu_\mu (\nu_e) \leftrightarrow \nu_X$ oscillations, where the ν_X is not seen: they are in some way similar, but obviously at much higher energies than those at nuclear reactors. Limits on the $\nu_e \leftrightarrow \nu_X$ oscillations of 55 eV^2 and 10 eV^2 at maximum mixing have been obtained by H. Deden et al., (Deden et al. 1981) and by N. Armenise et al. (1981a) at 90% CL, respectively.

A result of difficult interpretation which could imply neutrino oscillations have been obtained in the CERN beam dump experiments, where a 400 GeV proton beam has been dumped in a copper target to investigate neutrinos produced "promptly", namely very probably by the decay of charmed particles. It is expected that the electron and muon components of these neutrinos, after subtractions of the background of "normal" neutrinos produced by pion and kaon decay, be the same. On the contrary, the ratio between electron and muon "prompt" neutrinos was found to be (0.59 ± 0.3) and (0.48 ± 0.16) for the BEBC and charm experiments, while in the CDHS experiment the value ranges between (0.58 ± 0.19) and (0.77 ± 0.24) according the way the background has been subtracted (Boem 1980). This could be taken as evidence for neutrino oscillations, but some care should be devoted to the large errors, the possibility of other systematic effects, even in the background subtraction, and also to the fact that the neutrino sources are not perfectly known.

Various experiments which are specially dedicated to neutrino oscillations have been proposed at different accelerators. A search is being planned at Brookhaven (Sourkas et al. 1978, Mann 1981), where the AGS accelerator would be run at an energy of 800 MeV only, equal to the one at Los Alamos, and the average energy of the focused neutrino beam would be around 100 MeV. The detector, constructed for the Brookhaven neutrino experiment, consists of 32 planes of scintillator, interleaved with 31 drift chambers with a total mass of 172 t.

Three experiments at higher proton energy (from 12-19 GeV) are planned at the CERN PS by the Athens-Padova-Pisa-Wisconsin Collaboration, by the CDHS and by the CHARM Collaborations. The first one consists in the exposure of the BEBC bubble chamber filled with 75% neon and 25% hydrogen and

placed at 900 m from the target, to a focused neutrino beam produced by 12 GeV protons. The experiment is mainly intended to search for $\nu_\mu \rightarrow \nu_e$ oscillations, where a limit of $\Delta < 0.09 \text{ eV}^2$ at maximum mixing and of $\sin^2 2\alpha < 0.003$ at large Δ could be reached (Padova-Pisa-Athens-Wisconsin Collaboration 1980). Both CDHS (Rothberg 1981) and CHARM (1981) experiments, on the contrary, aim to search for a "disappearance" of muon neutrinos, namely for $\nu_\mu \rightarrow \nu_\tau$ oscillations. Since a good determination of the neutrino fluxes is especially required in this case, the use of two detector is planned in each experiment: one "near" ($\sim 100 \text{ m}$), the other "far" ($\sim 900 \text{ m}$) from the target. These experiments are in some way complementary: the CDHS one has a larger mass ($\sim 1000 \text{ t}$ for the "far" position), but poorer granularity (iron plates of 5 cm or more, interleaved with scintillators), while CHARM presents a better granularity (marble slabs of 8 cm thickness interleaved with drift chambers and limited streamer tubes), but only 135 t for the "far" detector. Limits of Δ between 0.25 eV^2 and 0.34 eV^2 for maximum mixing, and of $\sin^2 2\alpha < 0.1$ for large Δ are expected.

At much higher energies a similar proposal has been submitted to Fermilab by the CIT-Rockefeller-Fermilab-Colombia Collaboration (Schaewitz 1981). It is based on the use of two detectors at 650 and 1200 m from a target exposed to 400 GeV protons. Another proposal of the "missing neutrino" type has been submitted to CERN by the CERN-Imp. Coll.-Oxford-Annecy Collaboration (Grant et al. 1981), and is based also on the use of two detectors, one at 960 m from the target, and the other placed behind the Jura mountain at 17 km. The two detectors would be made by fine structure calorimeters followed by dipoles to analyze magnetically the outgoing penetrating charged particles. A sensitivity of $\Delta < 0.15 \text{ eV}^2$ should be reached at maximum mixing. A similar experiment at Fermilab has been suggested by D. Cline (1980b).

4.5 Atmospheric neutrinos

Searches for oscillations of atmospheric neutrinos has been suggested by various authors (see for instance Cline 1980a) and can profit of the large underground detectors presently being constructed to investigate nucleon stability (sect. 5). Atmospheric neutrinos are generated by pions, kaons and muon decays and are composed at the surface of the earth by

electron and muon neutrinos (one and two thirds, respectively). Neutrino oscillations could produce at large depths either a change in this ratio due to $\nu_\mu \rightarrow \nu_e$ oscillations, or a lack of muon or electron neutrinos due to $\nu_\mu(\nu_e) \rightarrow \nu_X$ oscillations. A possible lack of ν_μ neutrinos was in fact suggested by Barger et al. (1980).

Another effective method would be to investigate the up-down asymmetry of atmospheric muon neutrino events (Cline 1980a, Barger 1981). If oscillations occur, the "up" component being filtered by the earth (fig. 10) should be considerably lower than the "down" one.

5. NUCLEON DECAY

As pointed out in the introduction, the problem of nucleon stability, even if experimentally investigated since 1954, has become a "hot" topic only recently due to cosmological considerations and to the predictions of sometimes beautiful gauge theories. It is indeed unfortunate that the help that experimentalists receive from theory is still scarce. They do not know a priori if they have to design a more or less massive (and therefore expensive) detector, since nucleon decay lifetime is predicted within at least two orders of magnitude. Moreover, since theoretical evaluations of the branching ratios of the various decay channels are also rather uncertain, the experimentalist receives very limited hints on the detecting properties he has to request to his set-up.

The only methods totally independent on the type of decay are those based on radiochemical inspection for radioactive residues left by nucleon decays in a geologically old sample of rock. R.I. Steinberg and J.C. Evans (1977) for instance have suggested the spontaneous decay of a proton in ^{39}K , since the ^{38}Ar so produced has a 20% probability to give rise to ^{37}Ar . This nucleus, which decays with a lifetime of 35 days, can be searched with the same methods employed to reveal the reaction (23) produced by solar neutrinos (sect. 4.1). A lower limit of 10^{26} years on proton decays was set with this method (Fireman 1977 and 1979). One could also, with the same geological methods employed for double beta decay (sect. 3), search in a rock containing the (A,Z) nucleus for abnormal

isotopic abundance of the $(A-1, Z)$ and $(A-1, Z-1)$ isotopes as a consequence of neutron or proton decay, respectively. The sensitivity of this method is at present of 10^{25} year only (Evans and Steinberg 1977), but can perhaps be considerably improved with the use of new techniques (Primakoff and Rosen 1981).

Much better limits on nucleon decay in specific channels can however be obtained by very massive and heavily shielded set-ups used both as source and as detector of nucleon decay. The results obtained so far refers only to "non-dedicated" experiments, carried out in laboratories deep underground to investigate the penetrating component of cosmic rays. The most sensitive of these experiments has been carried out for more than three years by the Case-Withwaterand-Irvine Collaboration (Reines and Crouch 1975) in a mine at a depth of 3288 m, equivalent to 8900 m.w.e. (metres of water equivalent). The detector, made by ~ 20 t of scintillators plus flash tubes, could detect charged particles and particularly muons incident from the surrounding rock.

A re-examination of these results (Learned et al. 1979) allows to set lower limits ranging from 10^{29} to 10^{30} years for different branching ratios into the various channels. A small experiment where nucleon decays were searched inside a 500 kg scintillator, was carried out in the Mont-Blanc tunnel leading to a limit of 10^{29} years (Bergamasco and Picchi 1974).

Another non-dedicated experiment is being carried out by the Pennsylvania group at the Homestake Laboratory (South Dakota) placed at 4400 m.w.e. (Deakine et al. 1980). The set-up shown in fig. 11 consists in 36 Cerenkov modules of $2 \times 2 \times 1.2$ m³ with 34 liquid scintillators in anticoincidence to reduce the background by cosmic ray muons.

The apparatus detects the typical μ -e signature and is therefore sensitive to all nucleon decays which produce a muon directly or indirectly (e.g. by a pion decay). No evidence for nucleon decay was found with an upper limit which is at present (Steinberg 1981) 1.2×10^{30} years. Some results obtained in an old non-dedicated experiment in the Kolar Gold Field

Laboratory will be discussed, together with the result of the new Kolar Gold Field experiment, later on.

The dedicated experiments on nucleon decay presently being installed or planned are based on two different approaches: the calorimetric one, where the source consists in plates of massive material, interspaced with detecting planes (fig. 12) and the Cerenkov one, where the high speed secondaries of nucleon decays in a pool of water are detected via their Cerenkov light by means of a large number of photomultipliers (fig. 13).

5.1 The background

Before entering into a discussion of the various experiments I would like to consider briefly the problem of background, which is always relevant in nucleon decay experiments, even when they are placed deep underground. There are at least four components of it: natural radioactivity, cosmic ray muons, neutrals from the rock and atmospheric neutrinos.

The radioactivity in underground caves is usually somewhat higher (a few times) than in normal laboratories at sea level, mainly due to the ^{235}U , ^{238}U and ^{232}Th chains in the rocks. It does not simulate nucleon decay since the energy of gamma rays, and even of neutrons produced by spontaneous fission in the rock, rarely exceeds a few MeV. In a big detector, however, the counting rate could be considerable and require improved triggering techniques and/or some shield around the set-up.

Cosmic ray muons produced by pion and kaon decay in the atmosphere are strongly suppressed at large depths (Crouch et al. 1978), where they are strongly peaked around the vertical. They may represent a source of background in nucleon decay experiments either directly, or indirectly, due to the neutral particles produced by their interactions in the rock. Their intensity does not depend only on the vertical thickness, but also on the shape of the mountain above the laboratory. I have calculated roughly the rate of muons entering a cube of 10 m side, taking into account, when available, the shape of the mountain, and reported them in table 1.

For all low depth american sites of which the profiles are not available, but which should be similar, I have taken the experimental figure given by D. Cline (1980) for the Silver King Mine (Utah). My figures for Mont-Blanc and Frejus agree within 50% with the results of measurement actually carried out there (Battistoni et al. 1979a, Barloutaud et al. 1981), while for Kolar Gold Field I have taken the value predicted by the Indian-Japanese Collaboration (Krisnaswami et al. 1980), which has been recently found in very good agreement with the experimental results (Miyake et al. 1981). The values in table 1 should be correct within a factor of two and agree, within this limit, with similar calculations by D. Perkins (1979).

Interactions in the detector by neutrons and kaons produced by muons in the rock and unaccompanied by charged particles entering contemporarily in the set-up can in principle simulate nucleon decays. There are no measurement on these high energy neutrals whose rate should however range between 10^{-3} to 10^{-4} times the muons entering the apparatus (Perkins 1979). Their background should therefore be lower than the unavoidable one due to atmospheric neutrinos at depth of more than ~ 4000 m.w.e.

Neutrinos can come from the sun, from gravitational collapses and from the decays of muon, pion and kaon produced by high energy cosmic ray interactions in the atmosphere. The first two sources of neutrinos do not represent a problem for nucleon decay experiments, since their energy is of a few MeV or of a few tens of MeV, respectively. In fact, the study of neutrinos from gravitational collapse could represent a very interesting subproduct of experiments on nucleon stability.

The rates of events induced by atmospheric neutrinos, which could represent the ultimate limit to experiments on nucleon decay, have been calculated in some detail (Fiorini 1980) and are at present being studied experimentally by the Nusex Collaboration. We would only like to remind here that their flux is mainly horizontal (65%) and that, unlike accelerated neutrinos their electronic component is as large as 30%. The expected neutrino event rate is of ~ 0.3 interactions per ton per year, of which almost two thirds are muonic, and more than a third muonless (electric charged current events and electron and muon neutral current events). Most (60-70%) of the muonic events consist in a single muon accompanied by low

energy hadrons which are not detected in most of the planned experiments. Only $\sim 30\%$ of all events have a visible energy above 500 MeV and only 10% of the total rate is accounted for by events with a visible energy compatible within 20% with that of nucleon decay. A further suppression of this background can be accomplished by an inspection of the kinematical features of the events, and is at present being studied experimentally at CERN by the NUSEX Collaboration. It seems however very difficult, at least to me, to reach with the present techniques sensitivities on proton decays much larger than $10^{3.2}$ years.

5.2 Experiments with calorimetric methods

Two experiments on nucleon decay based on calorimetric methods are present in construction and a third one is already running.

An experiment by the Minnesota-ANL Collaboration is located in the Soudan Mine Laboratory (Minnesota) (Marshak 1980, Shupe 1981) at a depth of 1900 m.w.e. (fig. 14).

The set-up consists of 3456 proportional tubes with iron walls of 1.5 mm thickness inside a special type of concrete (taconite) which is available on place and contains a considerable percentage of iron (average density of ~ 3.3 g). The set-up with a total mass of ~ 30 t, is due to start operation soon, and is mainly intended as a test apparatus in view of the planned construction, together with the Oxford group, of a 1000 t detector to be installed in the same mine.

The NUSEX experiment, proposed by the Frascati, Milano and Torino groups (Battistoni et al. 1979a) is at present being constructed in collaboration with CERN to be mounted in a laboratory placed in the Mont-Blanc tunnel between Italy and France (fig. 12) at a depth of more than 500 m.w.e. (Fiorini 1979b).

The set-up consists in a cube (fig. 12) of 3.5 m side made of 1 cm thick iron plates interspaced with planes of limited streamer tubes of 3.5 m length and 1×1 cm² section. This technique, recently developed in Frascati (Battistoni et al. 1979b), consists in operating a tube of Geiger type with a highly quenching mixture (e.g. 75% isobutane and 25%

argon) and a large diameter (50-100 μm) anode wire, in order to limit the discharge in a few millimetres region inside the tube. The principle of the NUSEX detector is to use the high tension wire just to produce the discharge in a plastic tube varnished inside with graphite acting as cathode. The pulse is then collected by a system of X-Y bidimensional strips (fig. 15). The total mass of the detector is 156 t with 47 000 wires and 94 000 readout channels. The resolution in energy is of $\sim \pm 20\%$ for the $\pi^0 e^+$ decay; but obviously better for all the decays where charged secondaries stop in the detector.

In order to test the system, a reduced scale detector of $3.5 \times 1 \times 1 \text{ m}^3$ has been built and exposed at CERN to pion and electron beams of momenta ranging from 150 to 2000 MeV/c. The two views of a pion and electron track are shown in figs 16 and 17 respectively. The larger hit multiplicity in the Y view is due to the fact that the strips are orthogonal to the wires.

The model has also been exposed at CERN to an unfocused neutrino beam obtained by dumping 10 GeV protons on a 60 cm long, 1 cm diameter Berillium target. The spectrum of these neutrinos is in fact almost exactly the same as the one by atmospheric ones. Up to now ~ 500 neutrino events have been observed with the neutrino beam orthogonal to the iron plates; about the same number is going to be collected at an incident angle of 45° . Some of these events are shown in fig. 18.

The only dedicated nucleon decay experiment running at present is the one by the Tata-Osaka-Tokio Collaboration in the Kolar Gold Field Laboratory at a depth of 7600 m.w.e. (Krisnaswani et al. 1980). The detector (fig. 19) consists of 34 planes of iron proportional counters of $10 \times 10 \text{ cm}^2$ section and 2.2 mm thick walls, mounted in alternative layers and interleaved with 1.3 cm thick iron plates.

The total and fiducial masses are 140 and 100, respectively. The planes totalling 1600 tubes are operated in five fold coincidence of any five layers, in order to avoid spurious counting due to radioactivity (30 and 10 counts per second for the external and internal tubes, respectively). The apparatus has at present been operated for five months with the detection of 223 muons crossing the detector (Miyake et al. 1980),

one muon stopping inside, a multiple muon event (beautiful!), eight horizontal muons from neutrino interactions in the rocks, three neutrino interactions inside the detector and three events that these authors do not interpret as neutrino or muon interactions and which could therefore be candidates for nucleon decay. Two similar events were found in a preceeding non-dedicated experiment. One has however to point out that none of these events is totally confined in the detector and that, also due to poor granularity, one has to wait new events and the results of better granularity experiments (like NUSEX) to clearly establish the origin of these undoubtedly interesting events.

5.3 Experiments based on the Cerenkov light

Two Cerenkov detectors, in addition to the already described Homestake set-up, are presently being built, both in the USA.

One of them by the Harvard-Purdue-Wisconsin Collaboration is going to be mounted in the Silver King Mine near Park City (Utah) at ~ 1700 m.w.e. (Blandino et al. 1980, Cline 1980, Wilson 1981). The detector, whose design has been changed recently, consists of a cylindrical water tank with vertical axis, with 11.3 m diameter and 7 m high containing photomultipliers which are mounted inside (and not on the walls) the active volume at a distance of ~ 1 m one from another. A veto counter made of drift tubes is going to be placed around the water tank to reduce the effect of atmospheric muons which are expected to cross the detector at a rate of about one per second. The detector of 760 t total mass is expected to become operational at the end of this year.

The largest detector on nucleon decay is being built by the Irvine-Michigan-Brookhaven Collaboration (Goldhaber et al. 1980, Van der Welde 1980, Sinclair 1981) in the Morton Salt Mine (Ohio) at 1670 m.w.e. It consists in a pool of $22.5 \times 17 \times 18$ m³, excavated in the salt and lined with two thick sheets of plastic to be filled with highly purified and continuously filtered water. The Cerenkov light will be detected by means of 2048 photomultipliers (fig. 20) immersed in the water near the walls.

Their time resolution (5 ns) should allow to recognize the position of the origin on an event inside the active volume with a precision of about

one metre. The background problems of this detector are considerable: it is exposed to about three muons per second and to a considerable number of neutrals produced by muons in the rock. For this reason the external region of the active volume is going to be used as an anticoincidence layer of a thickness to be defined when the detector will be operational (end of this year). The final fiducial volume will range between 1600 and 4000 t.

5.4 Experiments presently being planned

Various other nucleon decay experiments have been designed and are under consideration by the national funding authorities. A 1.5 kiloton calorimeter has been proposed by the Orsay-Palaiseau-Paris-Saclay Collaboration, to be run in a laboratory situated in the Frejus tunnel between France and Italy at a depth of ~ 4000 m.w.e. (Bareyre et al. 1980). It would consist in a sandwich made by 3 mm thick iron plates interspaced with 5.5 mm thick flash chambers of the type developed by M. Conversi (Conversi and Federici 1978, Ceradini et al. 1978, Conversi and Lacava 1979, Conversi 1980). The trigger will be provided by 200 planes of Geiger counters. The readout system has not yet been finalized and three options are being considered: optical readout with film or with video cameras, and magnetostriuctive readout.

A similar proposal for a second generation experiment has been submitted to the Italian authorities (Frascati-Milano-Roma-Torino 1980). The planned detector is a calorimeter of 4 to 6 kilotons, with limited streamer tubes and flash chambers to be installed in the Gran Sasso tunnel, in central Italy. The French and Italian proposals are in strict connection and both open to international collaborations.

Two proposals have been submitted to funding authorities in Japan. One, by the KEK-Tokio-Tsukaba Collaboration 1981 is based on the construction of a cubic water Cerenkov detector of 14 m side viewed by very large and recently built photomultipliers of 50 cm diameter. The other, by the KEK-Osaka-Tokio Collaboration consists in the construction of a calorimeter with 5 mm thick iron plates interspaced with planes of flash chamber. The trigger will be accomplished with scintillators or multiwire proportional chambers. Masses of 600 and 1200 t are considered for the first and second generation experiments respectively.

Plans for nucleon decay experiments are also being considered in the Soviet Union (Goldhaber 1980, Weinberg 1981a).

6. EXPERIMENTS ON NUCLEON-ANTINUCLEON OSCILLATIONS

Nucleon-antinucleon oscillations have been suggested by many authors (Kuzmin 1970, Glashow 1979 and 1980, Marshak and Mohapatra 1980, Chetyskin 1980 and Chang 1980), also on the basis of cosmological considerations (Sawada et al., 1980), to test baryon non-conservation in the specific $\Delta B=2$ channel. According to these authors real neutron states would consist in a mixture of "pure" neutron and antineutron fields, and $n - \bar{n}$ oscillations could occur (Baldo Ceolin 1980a and 1980b, Yoshicki 1980 and Green 1981) with a "free" neutron-antineutron oscillation time

$$\tau_{nn} = \frac{1}{g_{\Delta B=2}}, \quad (34)$$

where $g_{\Delta B=2}$ is the amplitude of the $\Delta B=2$ process.

In the ideal (and unrealistic) case of free neutrons, the "real" particles would be

$$|n_1\rangle = \frac{1}{\sqrt{2}} |n\rangle + \frac{1}{\sqrt{2}} |\bar{n}\rangle, \quad (35)$$

$$|n_2\rangle = -\frac{1}{\sqrt{2}} |\bar{n}\rangle + \frac{1}{\sqrt{2}} |n\rangle, \quad (36)$$

where $m_{1(2)} = m_0 \pm \Delta m$, and $\Delta m \sim 10^{-22}$ eV.

This hypothesis is however never verified in practice, since the earth magnetic field (or even nuclear interactions if neutrons are not in vacuum) cause an energy split and the neutron (antineutron) energies become $E_0 \pm \Delta E$. The mixing between neutron and antineutron states becomes

$$|n_1'\rangle = \cos\theta |n\rangle + \sin\theta |\bar{n}\rangle \quad (37)$$

$$|n_2'\rangle = \sin\theta |n\rangle - \cos\theta |\bar{n}\rangle \quad (37)$$

$$\text{with } \text{tg}\theta = \frac{\Delta m}{\Delta E + \sqrt{(\Delta E)^2 + (\Delta m)^2}}.$$

An initially pure neutron beam of intensity $I(n,0)$ would therefore contain, after a time t , an $\bar{n}$ impurity of intensity

$$I(\bar{n},t) = I(n,0) \frac{(\Delta m)^2}{(\Delta m)^2 + (\Delta E)^2} [1 - \cos^2 (\sqrt{(\Delta E)^2 + (\Delta m)^2} \cdot t)] \quad (39)$$

The main contribution to ΔE , at least in the experiments planned so far, comes from the effect of the earth magnetic field on the neutron (antineutron) dipole magnetic moment and is of $\sim 6 \times 10^{-16}$ eV. It is therefore obvious from reaction (39) that the earth magnetic field has to be strongly degaussed, for instance by means of a shield of μ metal. From eq. (39), moreover, two experimental approaches appear to be possible in principle.

- (a) To try to keep neutrons under observation for a very long time. In this case the argument of the cosinus is very large and reaction (39) becomes

$$I(\bar{n},0) = I(n,0) \cdot \left(\frac{\Delta m}{\Delta E}\right)^2 \quad (40)$$

- (b) To accept a reasonably short observation time. In this case, if ΔE is also small (quasi-free neutron condition) eq. (39) becomes

$$I(\bar{n},0) \sim I(n,0) \Delta m^2 \cdot t^2 = I(n,0) \left(\frac{t}{t_{nn}}\right)^2 \quad (41)$$

and the $\bar{n}$ impurity does not depend anymore on ΔE .

Experiments on n - $\bar{n}$ oscillations can be in principle carried out with three types of neutrons:

- (a) thermal neutrons with speed of $\sim 1000 \text{ m s}^{-1}$ as those generated by a nuclear reactor;
- (b) cold neutrons with a speed of $\sim 100 \text{ m s}^{-1}$ as those obtained by a passing thermal neutrons through liquid hydrogen;
- (c) ultracold neutrons with energies $\sim 10^{-7}$ eV and a speed of a few metres per second (Golub and Pendlebury 1979).

The only experiment presently in operation is the one carried out by the CERN-Grenoble-Padova-Rutherford-Sussex Collaboration (Baldo Ceolin 1980b, Green 1981) at the ILL reactor in Grenoble, where an excellent beam of cold neutrons is available. This beam is brought to the detector from the reactor by means of a 9 m long curved guide, where cold neutrons are reflected by the walls with limited losses, at least in the very low energy region. The beam, with a total intensity of 10^9 neutrons per second and an energy spectrum from 10^{-3} to 10^{-4} eV collides on a ^6Li target at the end of a 3 m long vacuum pipe (fig. 21), where the magnetic field is degaussed by a factor of $\sim 10^{-4}$ by means of a shield of μ metal.

The detector, with a total mass of 2/3 of a ton is made, at present, by 1000 tubes interleaved with scintillators to reveal the decay products of antineutron annihilation in an energy range between 0.3 - 1.3 GeV. Due to the presence of the curved neutron guide the set-up is not directly exposed to the reactor and the main background comes therefore from cosmic ray despite a heavy shield of iron, concrete and scintillation counters in AC (anticoincidence). The experiment aims to reach the limit of 5×10^6 s on the free nucleon-antinucleon oscillation time, which would correspond to the present limit of $\sim 10^{30}$ years from nucleon decay experiments.

Other experiments are planned with thermal neutrons by the Harvard-Oak Ridge-Tennessee Collaboration (Cohn 1981, Green 1981) by the Pavia-Rome Collaboration, possibly in collaboration with the National Bureau of Standards (Pavia-Roma 1980, Green 1981) and by LAMPF (Green 1981), while two experiments, one with thermal and one with ultracold neutrons are planned in Japan. Ultracold neutrons have in fact been proposed (Yoshicki 1980, Baldo Ceolin 1981b) due to their very long wavelength (of up to a thousand $\text{\AA}$) which prevents them to penetrate the walls of the "neutron bottle", where they could therefore be kept for very long times. There are, however, many problems: hydrogen contamination on the walls could warm the neutrons up and allow them to leave the bottle, reflection on the walls would alter the phase shift between the $|n\rangle$ and $|\bar{n}\rangle$ states, the total number of neutrons that can be kept in the bottle is very small, etc.

7. CONCLUSIONS

I would like to conclude this admittedly incomplete review with the following considerations:

- (i) There are for the first time considerable hints that the neutrino mass be different from zero. These hints have to be confirmed or disproved as soon as possible.
- (ii) No evidence has been found for violation of any type of lepton flavour and very impressive experimental limits have been set, which could perhaps be better exploited by theory.
- (iii) Evidence has been obtained for the existence of two neutrino double beta decay, but no evidence yet for the neutrinoless lepton violating process. New experiments are planned and they will hopefully bring results which can be very relevant also to the problem of neutrino mass. Improved theoretical calculations are urgently needed especially on nuclear matrix elements not only for a correct interpretation of the results, but also to address the experimentalists on the more promising isotopic triplets to be searched for double beta decay.
- (iv) Various experiments in a wide range of energies and with totally different techniques are being carried out on neutrino oscillations and should tell us soon if the hints on the existence of this process from the Savannah River reactor represent indeed the first evidence for oscillations.
- (v) There is no evidence yet on nucleon decay, apart three candidates presented by the Kolar Gold Field Collaboration. These unusual events have to be found also in the larger and better grain detectors presently being built, which should be capable to provide for them an unambiguous interpretation.
- (vi) Neutron-antineutron oscillation experiments could be very useful in association with those on nucleon decay to clarify the nature of baryon violating processes.

- (vii) None of the experiments reported in this review requires specifically very high energies. This could perhaps represent a refreshing low energy pause in the run towards more and more powerful accelerators.
- (viii) Some of these experiments are very cheap, other are not, but very rarely they are as expensive as those at the high energy machines. On the contrary, they are always on the limit of technical feasibility and require considerable experimental ingenuity and imagination.
- (ix) Most of these experiments require a good knowledge of subjects other than elementary particle physics like astrophysics, geology, nuclear and reactor physics, low temperature physics, optics etc. This is very appealing for an experimentalist: it would be wonderful if the present experimental and theoretical efforts would bring not only to unification of strong and electroweak forces, but also to some type of "unification" in the experimental approach and in the use of different techniques to reach the same goal.

This paper is dedicated, with gratitude and sorrow to the memory of Carlo Franzinetti, an outstanding physicist, a devoted teacher and a dear friend.

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TABLE 1

Muon background in a cubic detector of 10 m side

Location	Nature of the site	Vertical depth (in m.w.e.)	Muon background (per year)
Simplon (Europe)	Railway tunnel	5600	50 000
Mont-Blanc (Europe)	Highway tunnel	5200	17 000
Frejus (Europe)	Highway tunnel	4200	500 000
St-Gothard (Europe)	Highway tunnel	3700	800 000
Gran Sasso (Europe)	Highway tunnel	4000	500 000
Homestake (USA)	Gold mine	4400	800 000
Kolar Gold Field (India)	Gold mine	7600	3000
Morton, King and Soudan (USA)	Mines	1800	30 000 000

FIGURE CAPTIONS

- Fig. 1 (a) The measured beta spectrum by Lyubimov et al. The external curves represent the error limits on the neutrino mass.
- (b) The experimental distribution of the values of the neutrino masses. The curves 1 and 2 refer to zero and 35 eV, respectively.
- Fig. 2 A cross section of the Mont-Blanc tunnel and position of the laboratory.
- Fig. 3 Contributions of ^{239}Pu , ^{235}U and ^{238}U to the reactor anti-neutrino spectrum.
- Fig. 4 Experimental apparatus of the CIT-Grenoble-Munich Collaboration.
- Fig. 5 Comparison between the Savannah River and Grenoble experiments on neutrino oscillations.
- Fig. 6 The beam dump neutrino layout at LAMPF.
- Fig. 7 The experimental set-up by Bowman et al.
- Fig. 8 The result on neutrino oscillations by the experiment by Bowman et al.: (a) D_2O filling and (b) H_2O filling.
- Fig. 9 The results on oscillations by the Gargamelle Collaboration.
- Fig. 10 The use of an underground detector to detect oscillations of atmospheric neutrinos (Cline 1980a).
- Fig. 11 The Homestake nucleon decay detector.
- Fig. 12 Artist's view of the NUSEX nucleon decay detector (by E. Iarocci).
- Fig. 13 The use of Cerenkov light to detect nucleon decay (in the $\pi^0 e^+$ mode).

FIGURE CAPTIONS (Cont'd)

Fig. 14 The Minnesota experiment on nucleon decay.

Fig. 15 The X-Y readout system of the NUSEX experiment.

Fig. 16 A 500 MeV/c π^- in the NUSEX apparatus.

Fig. 17 A 500 MeV/c electron in the NUSEX apparatus.

Fig. 18 Two neutrino events in the NUSEX apparatus.

Fig. 19 The Kolar Gold Field set-up.

Fig. 20 The Irvine-Michigan-Brookhaven detector.

Fig. 21 The CERN-Padua-Rutherford-Sussex detector for neutron-antineutron oscillations.

Fig. 1

IRAFORO DEL MONTE BIANCO

Sezione Longitudinale

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8 a

Fig. 8 b

Fig. 9

ATMOSPHERE-
SOURCE OF MUON NEUTRINOS)

P
COSMIC RAYS

NEUTRINO OSCILLATIONS:

MEASURE $\frac{\nu_e \text{ FLUX}}{\nu_\mu \text{ FLUX}}$ AS FUNCTION
OF L , THE DISTANCE FROM SOURCE.

Fig. 10

Fig. 11

NUCLEON **S**TABILITY **EX**PERIMENT
FRASCATI - MILANO - TORINO

Fig. 12

Fig. 13

Fig. 14

Fig. 15

EVENT # 43
500 MEV/C P1-

Fig. 16

EVENT # 23
500 MEV ELECTRON

Fig. 17

Fig. 18

FIGJ: FRONT VIEW OF PROTON STABILITY DETECTOR IN K.G.F (7600 FEET)

Fig. 20

Fig. 21