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Experiments on lepton and baryon stability and oscillation phenomena

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The various experiments on lepton number conservation and on nucleon stability currently being done or prepared are reviewed, and their relative merits compared and discussed. The first part of the paper is devoted to the measurement of the neutrino 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 neutrinos. The second part of the paper concerns the few results and the many planned detectors on nucleon decay with particular emphasis on the problems of background radioactivity and of the variety of experimental approaches. Oscillation experiments on neutron–antineutron oscillations at nuclear reactors are also considered.

1. INTRODUCTION

Lepton and baryon numbers were never considered as sacred by experimentalist, and searches to reveal their violation have been done for almost fifty years (Weinberg 1981 *a*, *b*). Their non-conservation has been, on the other hand, suggested on cosmological or astrophysical bases, 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 neutrinos (Gribov & Pontecorvo 1969). Recently, however, a much larger experimental effort on these subjects has 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 & Ross 1979; Machacek 1979; Gaillard 1979; Wilczek 1979; Weinberg 1979; Weinberg 1980; Langaker 1980; Nanopoulos 1980; Pati 1980; Ellis 1980; Giorgi & Glashow 1981; Primakoff & Rosen 1981; Glashow 1981), and discussed in this meeting by J. Ellis & Abdus Salam. I am not concerned with them here, or with their cosmological implications (Sawada & Sugamoto 1979) which have been reviewed at this meeting by G. Steigman.

Let me just point out, as an experimentalist, that we should look for lepton and baryon stability with an 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. It is hoped, therefore, that not only will they test the validity of gauge theories, but they will also allow one to choose between the different models.

All of the 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. It is surprising that they only rarely require what has been the most obvious tool of elementary particle physics: accelerators of very high energy.

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

$$^{22}\mathrm{Na} \longrightarrow {}^{22}\mathrm{Ne} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \qquad (1)$$

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

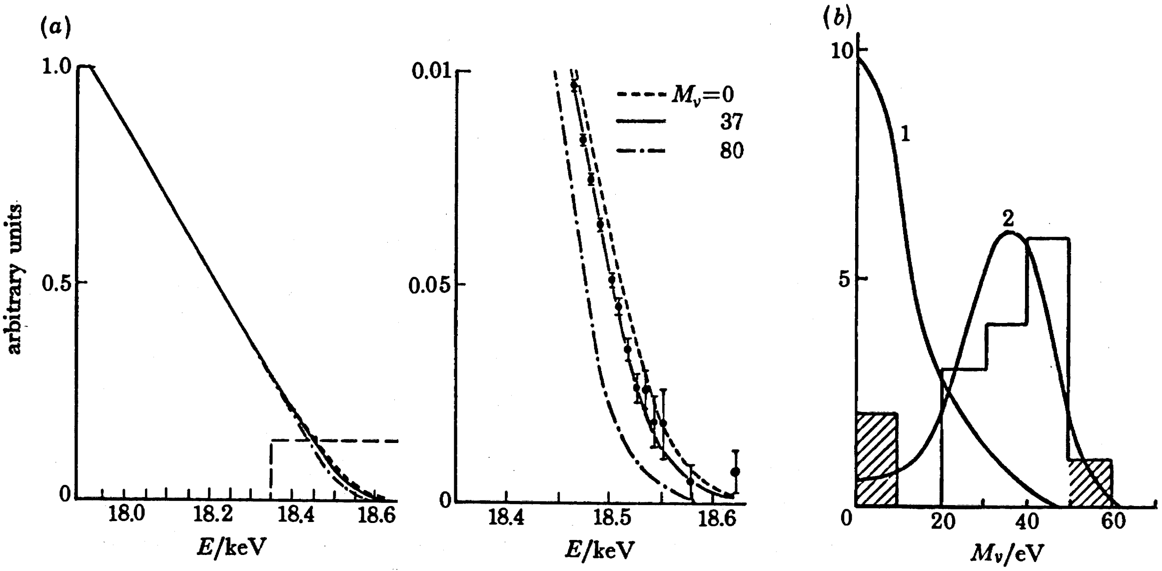

FIGURE 1. (*a*) The measured β-spectrum from Lyubimov *et al.* (1980, 1981). The —·—·— and ----- curves represent the error limits on the neutrino mass. (*b*) The experimental distribution of the values of the neutrino masses. The curves 1 and 2 refer to 0 and 35 eV, respectively.

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

$$^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}} \qquad (2)$$

with a transition energy that has been recently evaluated to be 18.567 ± 0.005 keV (Simpson 1981). Tritium experiments have so far been performed mostly 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. Until last summer all experimental results agreed with a zero mass, with upper limits around 50 eV (Simpson 1981). The common belief that this limit, of the order of atomic energies, could hardly be improved was contradicted by the result of an experiment made for more than five years by the Moscow group (Lyubimov *et al.* 1980, 1981). Electrons from a valine ($C_5H_{11}NO_2$) source of thickness 2 μg cm^{-2}, containing 18% tritium, were magnetically examined with a rotation angle of 720°. The end spectrum is clearly inconsistent with zero neutrino mass (figure 1) and indicates an electron antineutrino mass between 14 and 46 eV, at the 99% c.l. The authors themselves suggest some effects that could have simulated a non-zero neutrino mass, while others have been pointed out by Berkvist (1980): for example, the not completely correct use of the resolution function in the electron energy, the complexity of the valine molecule, and possible systematic errors in the parametrization of the electron spectrum. There is, however, no obvious effect that 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 other than magnetic spectrometry. One approach (Simpson 1981) consists of the high energy implantation of tritium nuclei into a Si(Li) detector to measure the β-spectrum directly. Another approach, suggested by A. de Rujula (Andersen *et al.* 1981), is based on the electron capture process

$$e^- + (A, Z) \longrightarrow (A, Z+1) + \nu_e + h\nu, \qquad (3)$$

which occurs in about 10^{-4} of all electron captures. The photon spectrum, which obviously has 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 of atomic or molecular effects. Nuclei like ^{157}Tb, ^{163}Ho and ^{193}Pt, which are of considerable interest for low transition energy and the shape of the photon spectrum in the high energy region, are going to be produced, in view of the experiment by the Moscow group, at the Isolde facility at CERN.

The relevance of a non-zero neutrino mass in the frame of grand unified theories and cosmology has been emphasized recently by Senjanovic (1981*a*, *b*), Mahopatra & Sejanovic (1981), Steigman (this symposium) and Ellis (this symposium), 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:

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

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% c.l.:

$$\mu^+ \longrightarrow e^+ + \gamma \qquad \leqslant 2\times 10^{-10} \qquad \text{(Bowman \textit{et al.} 1978);} \qquad (5)$$

$$\mu^- \longrightarrow e^+ + e^- + e^+ \qquad \leqslant 1.2\times 10^{-9} \qquad \text{(Korenchenko \textit{et al.} 1976);} \qquad (6)$$

$$\frac{\mu^- + {}^{32}S \longrightarrow e^- + {}^{32}S}{\mu^- \text{ capture}} \qquad \leqslant 7\times 10^{-11} \qquad \text{(Badertscher \textit{et al.} 1978; Boehm 1980).} \qquad (7)$$

Another interesting limit has been obtained:

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

This 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

$$\frac{\mu^- + {}^{127}\mathrm{I}\ \mathrm{e}^+ + {}^{127}\mathrm{Sb}}{\mu^-\ \text{capture}} \leqslant 3 \times 10^{-10} \qquad \text{(Abela } et\ al.\ \text{1980)} \qquad (9)$$

by searching for ^{127}Sb with radiochemical techniques.

The sensitivity of experiments on reactions (5) and (9) is going to be improved by two orders of magnitude in the near future at Los Alamos and Sin, respectively.

Experiments have also been made 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

$$\mu^+ \longrightarrow \mathrm{e}^+ \bar{\nu}_\mathrm{e}\, \bar{\nu}_\mu, \qquad (10)$$

and

$$\bar{\nu}_\mu + \mathrm{e}^- \longrightarrow \mu^- + \bar{\nu}_\mathrm{e}, \qquad (11)$$

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

$$\frac{\mu^+ \longrightarrow \mathrm{e}^+ \bar{\nu}_\mathrm{e}\, \nu_\mu}{\mu^+ \longrightarrow \mathrm{e}^+ \nu_\mathrm{e}\, \bar{\nu}_\mu} < 0.065 \qquad (90\%\ \text{c.l.}), \qquad (12)$$

$$\frac{\bar{\nu}_\mu \mathrm{e}^- \longrightarrow \mu^- \nu_\mathrm{e}}{\nu_\mu \mathrm{e}^- \longrightarrow \mu^- \nu_\mathrm{e}} < 0.09 \qquad (90\%\ \text{c.l.}). \qquad (13)$$

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

$$(\mathrm{A}, \mathrm{Z}) \longrightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\ \mathrm{e}^- + 2\bar{\nu}_\mathrm{e}, \qquad (14)$$

$$(\mathrm{A}, \mathrm{Z}) \longrightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\ \mathrm{e}^-. \qquad (15)$$

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

I do not enter here into a detailed description of the various experiments made so far (Fiorini 1977; Wu 1981) or on the various theories that have been constructed in the 'pre-gaugean' (Bryman & Picciotto 1978) or 'gaugean' eras (Vergados 1980; Primakoff & Rosen 1981). I just add a few comments on this very interesting topic.

The first concerns the experimental approach, which can be either of the 'geological' or of the 'direct' type. The former consists of 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 resulted in the only unambiguous evidence for double β-decay (for ^{82}Se, ^{128}Te and ^{130}Te).

It is, however, impossible to discriminate directly by geological methods between two-neutrino and neutrinoless decays, and hard to exclude the possibility that the abnormal abundance of the granddaughter nucleus could have been produced by processes other than double β-decay, e.g. interactions of cosmic rays and of solar neutrinos. 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 β-decay of the corresponding isotopes of tellurium (Hennecke 1978). Since the transition energies, for double β-decay of ^{128}Te and ^{130}Te are very different, and since therefore the theoretically determined rates depend strongly on the two-neutrino and neutrinoless hypothesis, the experimental ratio

$$^{128}\mathrm{Te}/^{130}\mathrm{Te} = (1.57 \pm 0.10) \times 10^{3} \tag{16}$$

can be usefully compared with theory.

Unambiguous evidence for neutrinoless double β-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 to search for the peak expected when no neutrino is emitted. No experiment so far has shown evidence for any type of double β-decay (Fiorini 1979*a*; Boehm 1980; Wu 1981), with the exception of the cloud chamber experiment by the Irvine group (Moe & Löwenthal 1980), where twenty candidates for two-neutrino double β-decay of ^{82}Se have been detected. The authors cannot, however, exclude the possibility that this sample could be due to radioactive background. Moreover, the obtained rate for double β-decay would be more than ten times that found by geological methods.

My second comment concerns the way double β-decay is evaluated theoretically. This process, in the neutrinoless channel, has been taken by 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 β-decay as a second-order sequence of two single β-decays. Neutrinoless double β-decay is then mediated by a virtual neutrino emitted by a nucleon and absorbed by another 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 & 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

$$\mathrm{n} \longrightarrow \mathrm{e}^- + \mathrm{e}^- + \Delta^{2+}, \tag{17}$$

and

$$\Delta^- \longrightarrow \mathrm{p} + \mathrm{e}^- + \mathrm{e}^-. \tag{18}$$

The rate would then be proportional to the inverse of the square of the radius of the nucleon, and therefore more than ten times that in the 'two-nucleon' mechanism. I have, however, to point out that resonances have been proved to be present in a small percentage inside the nuclei. The resonance contribution therefore seems small, and sometimes even negligible, at least in the two-neutrino channel (Doi *et al.* 1981*a*, *b*). It has probably been considered as important by Primakoff & Rosen because they 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 that nuclear matrix elements have been calculated in detail only in a few cases (Fiorini 1977; Vergados 1976; Haxton *et al.* 1980, 1981).

My third comment refers to the possibility of investigating double β-decay to an excited state of the (A, Z + 2) nucleus. Until a year ago all calculations on double β-decays have been made for the 0^+–0^+ transition between the ground states of the (A, Z) and (A, Z + 2) nuclei, with the only commendable exception being the work by Molina & Pascual (1977). Only recently have Rosen (1981) and Doi *et al.* (1981 *a*, *b*) considered, in the gaugean theories, transitions from the 0^+ ground state of the parent nucleus to excited states of the grand-daughter nucleus (the first excited level is always a 2^+). The 'minimal' conditions for the existence of neutrinoless double β-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.

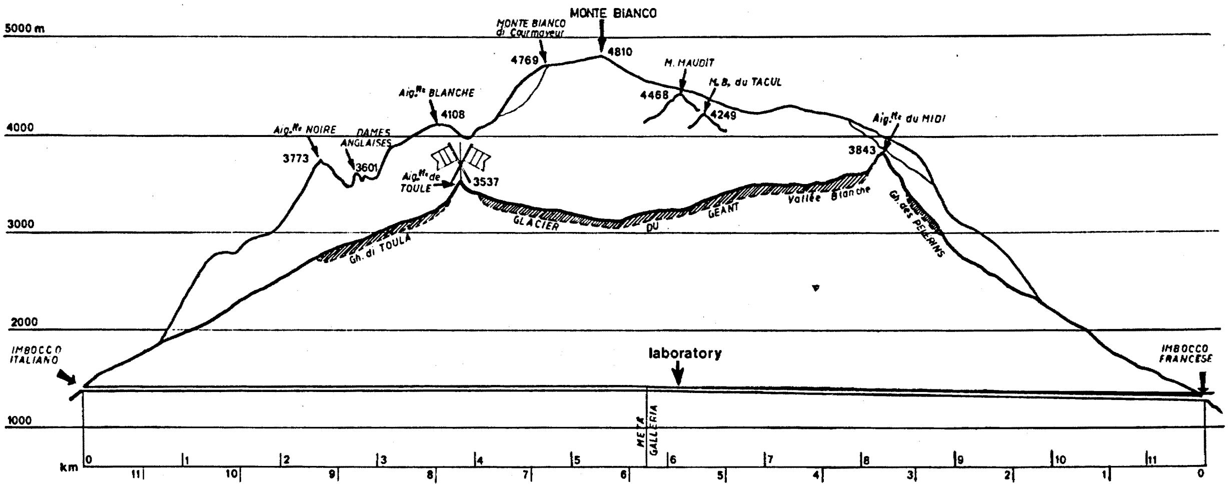

FIGURE 2. A cross section of the Mont-Blanc tunnel showing the position of the laboratory.

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 will be considered later. Double β-decay to an excited nuclear level, which then decays with emission of a γ-ray, is experimentally appealing. It has, however, been investigated until now only by the Milan group, who have set an upper limit of 3×10^{21} years (at 68% c.l.) for neutrinoless double β-decay of ^{76}Ge to the 2^+ excited state of ^{76}Se at 559 keV (Fiorini 1977). Various experiments have been suggested on double β-decay to excited nuclear levels (Fiorini 1978), and one of them, on the decay of ^{150}Nd to the 2^+ excited state of ^{150}Sm at 334 keV, is presently being made with a Ge(Li) set-up installed in a laboratory in the Mont-Blanc tunnel (figure 2). Until now there has been no evidence for two-neutrino or neutrinoless double β-decay to this excited level, with a lower limit on the half-life of 2×10^{18} years, at 68% c.l.

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 Doi *et al.* (1981 *a*, *b*). They 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 β-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 the two-neutrino decay seem inconsistent with the experimental ratio of the lifetimes of ^{128}Te and ^{130}Te, given in reaction (16), Doi *et al.* assume their experimental results to be positive evidence for lepton number non-conservation. In absence of right-handed current this leads to *positive* evidence for a massive neutrino with $m_\nu \approx 35$ eV.

This result is very interesting, but has to be treated 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, is *consistent* with the experimental ratio (16). Moreover, the same authors (Haxton *et al.* 1981), as well as 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 the absence of a right-handed current contribution. Comparison with the experimental data on Se and Ge 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 non-zero, oscillations should occur among electron, muon and tau neutrinos (Pontecorvo 1958; Bilenki & Pontecorvo 1978; Boehm 1980; Rosen & 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 between different models (Bilenki & Pontecorvo 1981). If we limit our considerations 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,

$$\nu_e = \nu_1 \cos\alpha + \nu_2 \sin\alpha, \tag{19}$$

$$\nu_\mu = -\nu_1 \sin\alpha + \nu_2 \cos\alpha, \tag{20}$$

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

$$P[\nu_\mu(\bar{\nu}_\mu)] = I(\overset{(-)}{\nu}_\mu)/I(\overset{(-)}{\nu}_e) = 0.5\sin^2 2\alpha[1-\cos(2.534\Delta D/E_\nu)], \tag{21}$$

where D is in m, 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.

Oscillation 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 of the distance of the source and the neutrino energy.

The experimental result can be interpreted by two extreme hypotheses:

(*a*) Large Δ-values. The cosine value is averaged to zero, and P gives a value of the mixing angle.

(*b*) Low Δ-values. A non-zero cosine value, or a limit on P, would involve both Δ and mixing angle.

Neutrino oscillations can, and have been, studied by 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

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow \mathrm{e}^- + {}^{37}\mathrm{Ar}, \tag{22}$$

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) n.s.u., where one n.s.u. corresponds to 10^{-36} neutrino captures per target nucleon per second, while the most recent theoretical predictions are larger by a factor of three to four (Bahcall 1980). This discrepancy cannot yet be taken, in my opinion, as evidence for neutrino oscillations among the various neutrino flavours, since theoretical prediction 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 for the new experiments on different neutrino targets, like those on the reaction

$$\nu_e + {}^{71}\mathrm{Ga} \longrightarrow \mathrm{e}^- + {}^{71}\mathrm{Ge}, \tag{23}$$

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

Considering the two 'sensitivity parameters' D/E and P, one notes that, while the average ratio D/E is very large (*ca.* 10^{11} m MeV^{-1}) in solar neutrino experiments, parameter P is badly determined, owing 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 are unknown. Moreover, contributions by ^{235}U, ^{238}U and ^{239}Pu are very different (figure 3).

Until a 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 $2 \times 10^{13}\,\bar{\nu}_e\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$ at 11 m from the centre of the core. A process that can be used to investigate neutrino oscillations is

$$\bar{\nu}_e + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n}, \tag{24}$$

where the e^+ was detected through its two annihilation γ-rays, and n by a suitable doping of the hydrogen-rich scintillator which acts also as a neutrino target. A possible lack of events in previous experiments (Sobel 1980) at 6.5 and 11.2 m from the reactor core has been reported, but could not be used as evidence for neutrino oscillation owing to uncertainties on the neutrino flux.

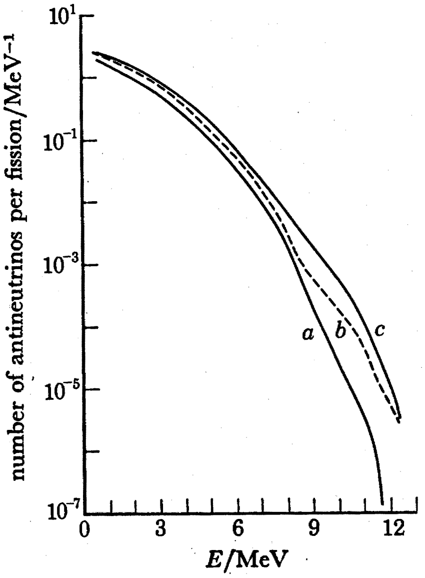

FIGURE 3. Contributions of (a) ^{239}Pu, (b) ^{235}U and (c) ^{238}U to the reactor antineutrino spectrum.

More recently an experiment was done at 11.2 m from the reactor core (Reines *et al.* 1980) on the charged and neutral current reactions

$$\bar{\nu}_e + \mathrm{d} \longrightarrow \mathrm{e}^+ + \mathrm{n} + \mathrm{n}, \tag{25}$$

$$\bar{\nu}_e + \mathrm{d} \longrightarrow \nu_e + \mathrm{p} + \mathrm{n}. \tag{26}$$

The ratio between these two processes is independent of the neutrino flux, but strongly dependent on the $\bar{\nu}_e \rightleftarrows \bar{\nu}_x$ 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 1980*a*, *b*; Silverman & Soni 1980) and critical remarks (Feynman & Vogel 1980; Dar 1980). Considerable attention was therefore focused on a new experiment made by the C.I.T.–Grenoble–München collaboration at the ILL reactor in Grenoble, where the neutrino intensity is lower ($9.8 \times 10^{11}\,\nu_e\,\mathrm{cm^{-1}\,s^{-1}}$ at 8.76 m from the centre of the core), but where one can profit from the typical advantages of an experimental reactor (a very small core, fuel made only by ^{235}U, better shielding, etc.). The experiment was made on the inverse β-decay reaction (24) with a detector made by 30 slabs of hydrogen-rich scintillator to detect the γ-rays from positron annihilation, interleaved with ^{3}He chambers to detect the neutron (figure 4).

The obtained spectrum is in good agreement with theoretical predictions in the 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 β-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 made by Davis and Vogel. The comparison between the two experimental results is shown in figure 5.

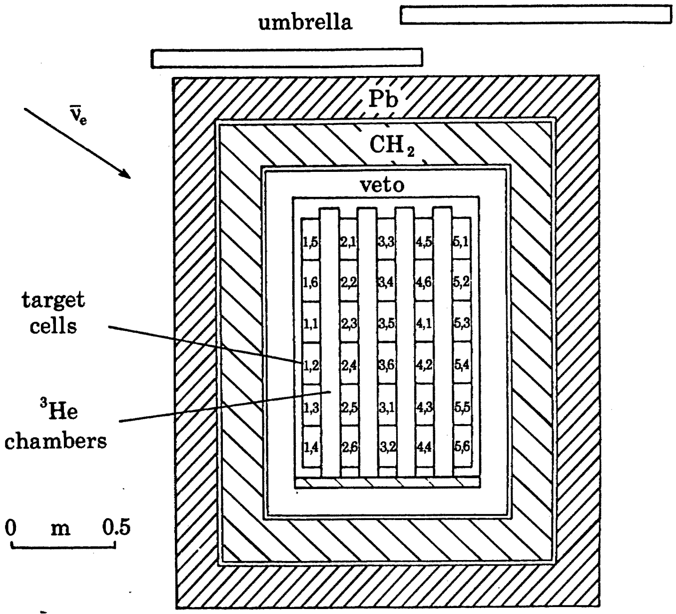

FIGURE 4. Experimental apparatus of the C.I.T.–Grenoble–München collaboration.

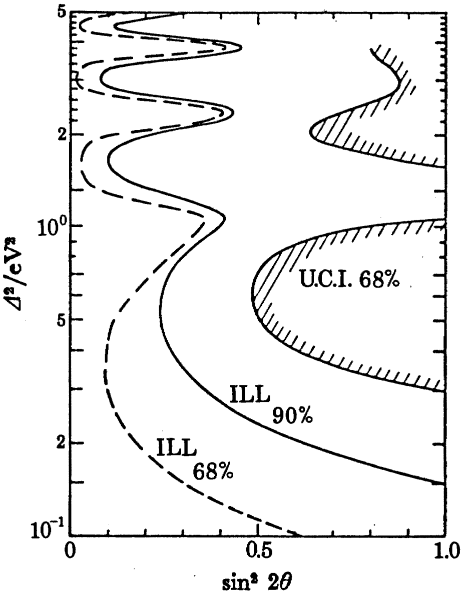

FIGURE 5. Comparison between the Savannah River and Grenoble experiments on neutrino oscillations.

I 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 distances is going to be done, by the C.I.T.–München collaboration at a 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 dense targets (figure 6). Since the π^- are absorbed, the following decays occur, if the additive law is valid:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu, \tag{27}$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu. \tag{28}$$

The only experiment on oscillations made so far is the one by Nemethy *et al.* (1981) at LAMPF, with a 6 m^3 Cherenkov detector, shielded with drift chambers against cosmic radiation (figure 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 D_2O, the ratio

$$R' = \nu_e/\nu_\mu = 1.09\{^{+0.37}_{-0.41}\} \tag{29}$$

was found for the reaction

$$\nu_e + d \longrightarrow e^- + p + p, \tag{30}$$

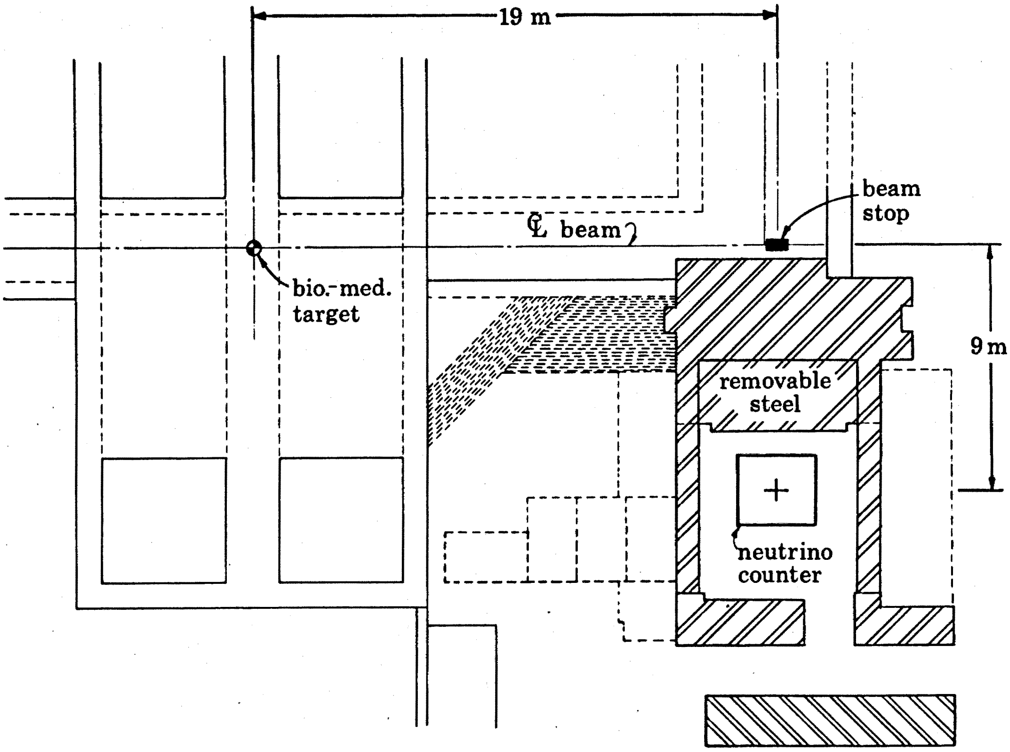

FIGURE 6. The beam dump neutrino layout at LAMPF. Scale: 1 cm ≡ 2.7 m.

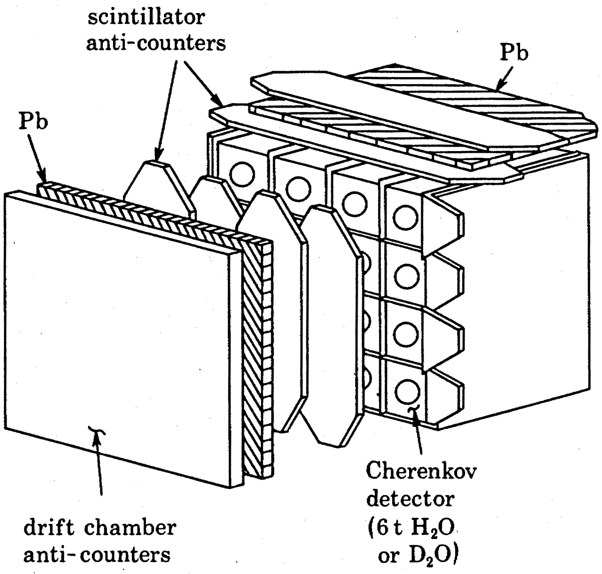

FIGURE 7. The experimental set-up of Bowman *et al.* (1979).

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while, by filling the detector with water, a ratio

$$R = 0.0001 \pm 0.061 \tag{31}$$

was found for the reaction

$$\bar{\nu}_e + p \longrightarrow e^+ + n. \tag{32}$$

The errors in reactions (29) and (31) include statistical and systematic errors. The dramatic change of counting rates when the filling is changed from D_2O to water can be seen in figure 8*a*, *b*.

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

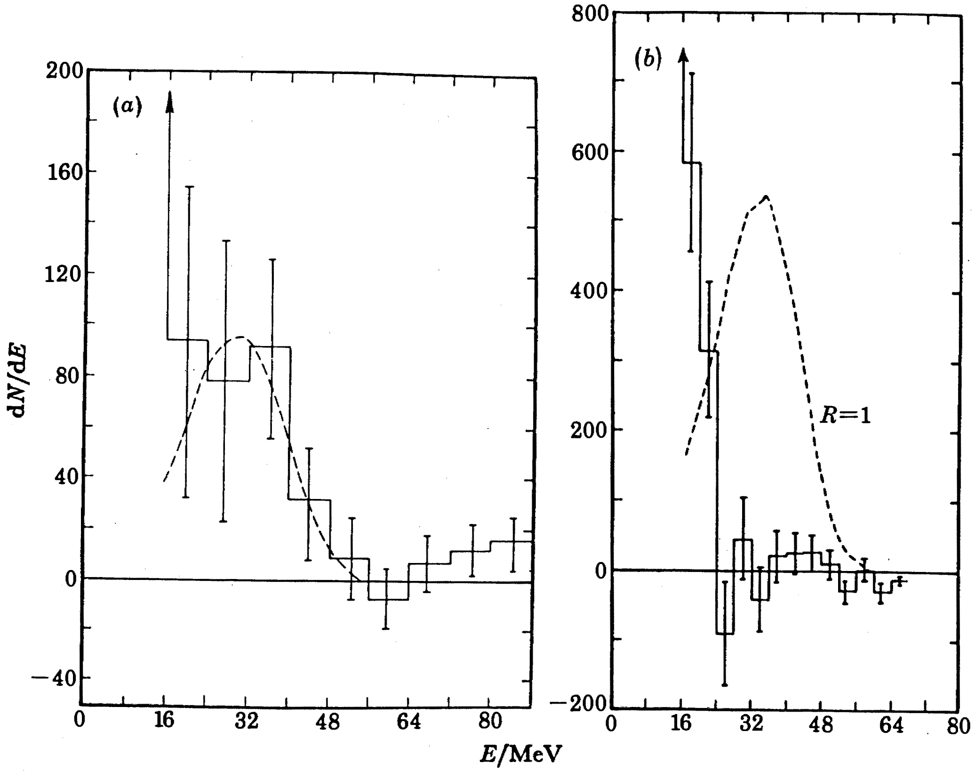

FIGURE 8. The results on neutrino oscillations from the experiment by Bowman *et al.* (1979): (*a*) D_2O filling; (*b*) H_2O filling.

Various new experiments are at present being considered at LAMPF to search for neutrino oscillations. Some of them are of the 'beam dump' type (Romanovski *et al.* 1980; Duon-Van *et al.* 1980); others are based on the use of a 'focused' neutrino beam, with a larger average energy (*ca.* 150 MeV) (Bowles *et al.* 1981; Ling *et al.* 1981; Mann 1981). The construction of a 150 m long, 5 m wide underground tunnel in which the detector could be moved (Duon-Van & Phyllips 1980), and even an 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

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(from a fraction of a percentage around 1 GeV to a small percentage at tens of gigaelectronvolts). If neutrino oscillations of the type $\nu_\mu \rightleftarrows \nu_e$ occur, an excess of electron neutrino events would appear in the detector, and the parameter P defined in equation (21) can be determined with good precision. The results of the Gargamelle collaboration (figure 9) show that, for maximal mixing parameter, $\Delta < 1\ \mathrm{eV}^2$.

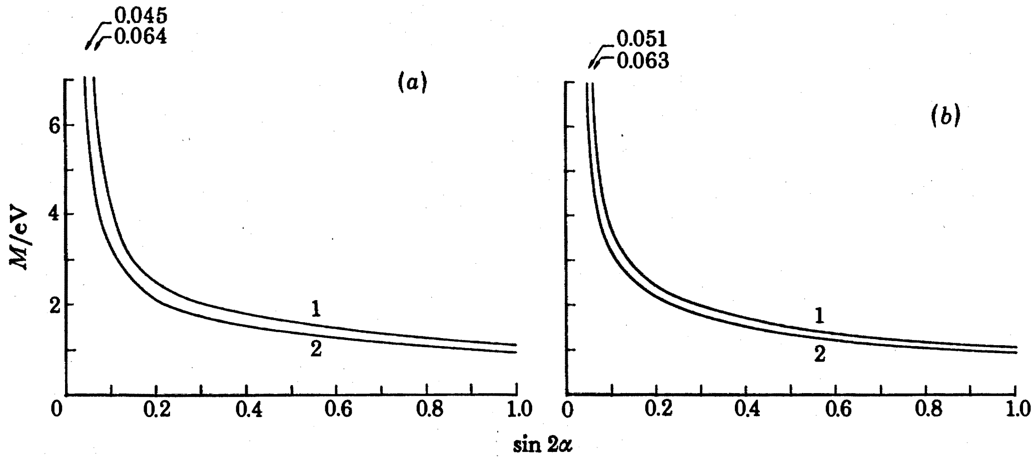

FIGURE 9. The results on oscillations obtained by the Gargamelle collaboration: (*a*) neutrino; (*b*) antineutrino. Curve 1, 68% c.l.; curve 2, 95% c.l.

Similar limits on $\nu_\mu \rightleftarrows \nu_e$ oscillations have been obtained in more recent bubble chamber (Cnops *et al.* 1978; Armenise *et al.* 1981 *a*, *b*) 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*, *b*) have searched for $\nu_\mu \rightleftarrows \nu_\tau$ oscillations, where the ν_τ neutrino interacts in the chamber, producing a tau lepton which is known to decay into an electron with a branching ratio of 20%, simulating an electron neutrino event. Limits of 6 eV², 3 eV² and 3.2 eV² have been obtained, respectively, for maximum mixing. An alternative approach for obtaining the same limit has been taken by Kondo *et al.* (1981), who searched directly for τ leptons 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 $\Delta \leqslant 3.5\ \mathrm{eV}^2$ at 90% c.l. has been obtained. Other experiments are of the 'missing neutrino' type, namely on $\nu_\mu(\nu_e) \rightleftarrows \nu_X$ oscillations, where the ν_X are not seen: they are in some ways similar to, but obviously at much higher energies than, those at nuclear reactors. Limits on the $\nu_e \rightleftarrows \nu_X$ oscillations of 55 eV² and 10 eV² at maximum mixing have been obtained at 90% c.l. by Deden *et al.* (1981) and by Armenise *et al.* (1981 *a*) respectively.

A result that is difficult to interpret, which could imply neutrino oscillations, has been obtained in the Cern beam dump experiments, where a 400 GeV proton beam was dumped in a copper target to investigate neutrinos produced 'promptly', very probably by the decay of charmed particles. It is expected that the electron and muon components of these neutrinos, after subtraction of the background of 'normal' neutrinos produced by pion and kaon decay, will 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 B.E.B.C. and CHARM experiments, while in the C.D.H.S. experiment the value ranges between 0.58 ± 0.19 and 0.77 ± 0.24, according to the way in which the background was subtracted (Boehm 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 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 A.G.S. accelerator would be run at an energy of 800 MeV only, equal to the energy 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 (12–19 GeV) are planned at the Cern PS by the Athens–Padova–Pisa–Wisconsin, the C.D.H.S. and by the CHARM collaborations. The first consists of the exposure of the B.E.B.C. bubble chamber, filled with 75% neon and 25% hydrogen and placed 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 limits 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 C.D.H.S. (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, it is planned to use two detectors in each experiment: one 'near' (*ca.* 100 m) to, the other 'far' (*ca.* 900 m) from the target. These experiments are to some extent complementary: the C.D.H.S. one has a larger mass (*ca.* 1000 t for the 'far' position), but poorer granularity (iron plates 5 cm thick or more, interleaved with scintillators), while CHARM presents a better granularity (marble slabs 8 cm thick interleaved with drift chambers and limited streamer tubes), but only 135 t for the 'far' detector. Limits of Δ between $0.25\ \text{eV}^2$ and $0.34\ \text{eV}^2$ 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 C.I.T.–Rockefeller–Fermilab–Colombia collaboration (Shaewitz 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–Imperial College–Oxford–Annecy collaboration (Grant *et al.* 1981), which is also based on the use of two detectors, one 960 m from the target, and the other placed 17 km from the target behind the Jura mountain. The two detectors would be made by fine-structure calorimeters followed by dipoles to analyse 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 Cline (1980*b*).

4.5. *Atmospheric neutrinos*

Searches for oscillations of atmospheric neutrinos have been suggested by various authors (see for instance Cline (1980*a*)) and can profit from the large underground detectors presently being constructed to investigate nucleon stability (§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, in proportions one and two thirds, respectively. Neutrino oscillations could produce at large depths either a change in these proportions 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 muon 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 1980*a*; Barger 1981). If oscillations occur, the 'up' component being filtered by the Earth (figure 10) should be considerably lower than the 'down' one.

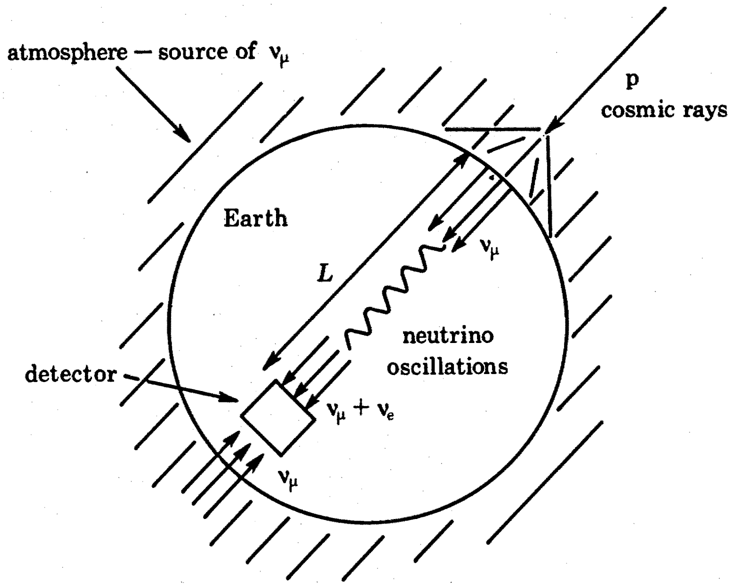

Figure 10. The use of an underground detector to detect oscillations of atmospheric neutrinos (Cline 1980*a*). The ratio of the fluxes of ν_e and ν_μ is measured as a function of L, the distance from the source.

5. Nucleon decay

As pointed out in the Introduction, the problem of nucleon stability, although experimentally investigated since 1954, has become a 'hot' topic only recently owing 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 larger or smaller (and therefore more or less expensive) detector, since nucleon decay lifetime is predicted within only 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 of the type of decay are those based on radiochemical inspection for radioactive residues left by nucleon decays in a geologically old sample of rock. Steinberg & 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 of giving rise to ^{37}Ar. This nucleus, which decays with a lifetime of 35 days, can be searched for by the same methods as used to reveal the reaction (22) produced by solar neutrinos (§4.1). A lower limit of 10^{26} years on proton decays was set with this method (Fireman 1977, 1979). One could also, with the same geological methods as used for double β-decay (§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 only 10^{25} years (Evans & Steinberg 1977), but can perhaps be considerably improved with the use of new techniques (Primakoff & 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 refer only to 'non-dedicated' experiments, made in laboratories deep underground, to investigate the penetrating component of cosmic rays. The most sensitive of these experiments has been made for more than three years by the Case–Witwatersrand–Irvine collaboration (Reines & 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 about 20 t of scintillators, and flash tubes, could detect charged particles and particularly muons incident from the surrounding rock.

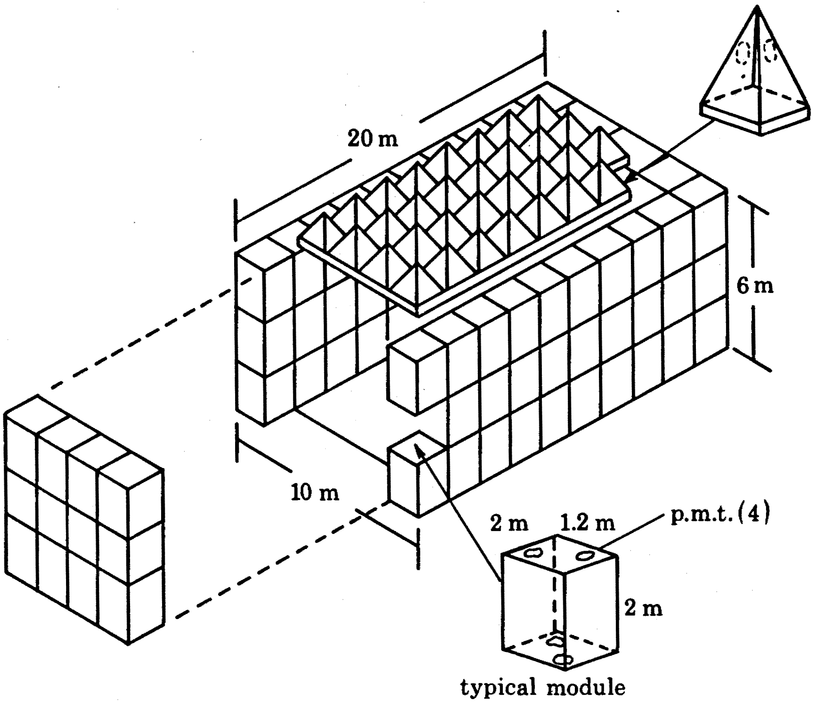

FIGURE 11. The Homestake nucleon decay detector.

A re-examination of these results (Learned *et al.* 1979) allows us 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 for inside a 500 kg scintillator, was made in the Mont-Blanc tunnel and lead to a limit of 10^{29} years (Bergamasco & Picchi 1974).

Another non-dedicated experiment is being made 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 figure 11 consists in 36 Cherenkov modules of $2 \times 2 \times 1.2$ m^3 with 34 liquid scintillators in anticoincidence to reduce the background of cosmic ray muons.

The apparatus detects the typical muon–electron signature and is therefore sensitive to all nucleon decays that produce a muon directly or indirectly (for example 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 in the paper.

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

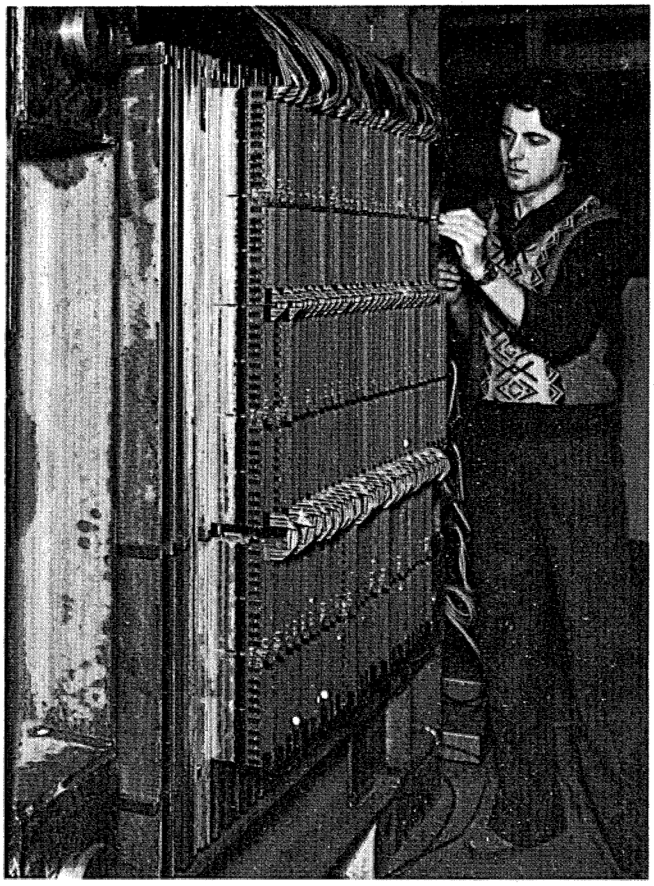

FIGURE 12. A model of the NUSEX nucleon decay detector.

5.1. *The background*

Before entering into a discussion of the various experiments I consider briefly the problem of background radioactivity, 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 higher (a few times) than that in normal laboratories at sea level, mainly owing to the ^{235}U, ^{238}U and ^{232}Th chains in the rocks. It does not simulate nucleon decay since the energy of γ-rays, and even of neutrons produced by spontaneous fission in the rock, rarely exceeds a few megaelectronvolts. In a big detector, however, the counting rate could be considerable and require improved triggering techniques or some shield around the set-up, or both.

Cosmic ray muons produced by pion and kaon decay in the atmosphere are strongly suppressed at large depths (Crouch *et al.* 1978), where their angular distribution is strongly peaked around the vertical. They may represent a source of background radioactivity in nucleon decay experiments either directly, or indirectly, owing 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 side 10 m, taking into account, when available, the shape of the mountain. The results are given in table 1.

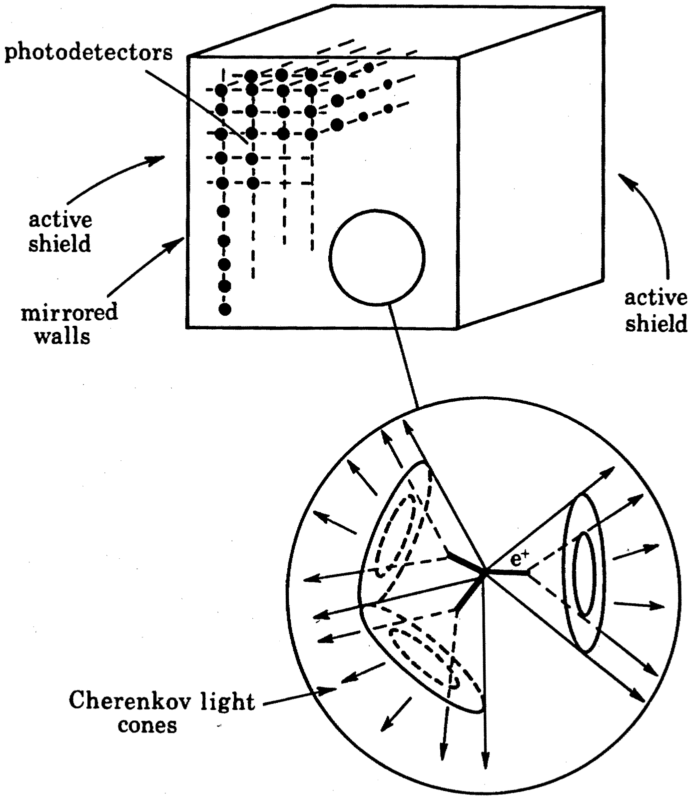

FIGURE 13. The use of Cherenkov light to detect nucleon decay (in the π^0e^+ mode).

TABLE 1. MUON BACKGROUND IN A CUBIC DETECTOR OF SIDE 10 m

location	nature of site	vertical depth (m.w.e.)	muon background / 10^3 year^{-1}
Simplon (Europe)	railway tunnel	5600	50
Mont Blanc (Europe)	road tunnel	5200	17
Frejus (Europe)	road tunnel	4200	500
Saint Gothard (Europe)	road tunnel	3700	800
Gran Sasso (Europe)	road tunnel	4000	500
Homestake (U.S.A.)	gold mine	4400	800
Kolar Gold Field (India)	gold mine	7600	3
Morton, King and Soudan (U.S.A.)	mines	1800	30000

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

Interactions in the detector of neutrons and kaons produced by muons in the rock and unaccompanied by charged particles entering contemporarily into the set-up can in principle simulate nucleon decays. There are no measurements on these high energy neutrals whose rate should, however, range between 10^{-3} and 10^{-4} times that for 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 about 4000 m.w.e.

Neutrinos can come from the Sun, from gravitational collapses and from the decays of muons, pions and kaons 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 megaelectronvolts or of a few tens of megaelectronvolts, 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. Let us recall here only that their flux is mainly (65%) horizontal and that, unlike accelerator neutrinos, their electronic component is as large as 30%. The expected neutrino event rate is about 0.3 interactions per tonne 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 of a single muon accompanied by low energy hadrons that are not detected in most of the planned experiments. Only about 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, at least to me, very difficult to reach with the present techniques sensitivities on proton decays much larger than 10^{32} years.

5.2. *Experiments with calorimetric methods*

Two experiments on nucleon decay based on calorimetric methods are now under construction and a third is already running.

An experiment by the Minnesota–A.N.L. collaboration is located in the Soudan Mine Laboratory (Minnesota) (Marshak 1980; Shupe 1981) (figure 14) at a depth of 1900 m.w.e.

The set-up consists of 3456 proportional tubes with iron walls of 1.5 mm thickness inside a special type of concrete (taconite) that is available on site and contains a considerable percentage of iron (average density of about 3.3). The set-up with a total mass of about 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.* 1979*a*) is at present being constructed in collaboration with Cern, and is to be mounted in a laboratory placed in the Mont-Blanc tunnel between Italy and France (figure 2) at a depth of more than 5000 m.w.e. (Fiorini 1979*b*).

The set-up consists of a cube of side 3.5 m made of iron plates 1 cm thick interspaced with planes of limited streamer tubes of length 3.5 m and section 1 × 1 cm^2. This technique, recently developed in Frascati (Battistoni *et al.* 1979*b*), consists of operating a tube of Geiger type with a highly quenching mixture (e.g. 75 % isobutane, 25 % argon) and an anode wire of large diameter (50–100 μm), to limit the discharge to a region of a few millimetres 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* two-dimensional strips (figure 15). The total mass of the detector is 156 t with 47 000 wires and 94 000 readout channels. The resolution in energy is approximately ± 20 % for the π^0e^+ decay, but obviously better than this for all the decays where charged secondaries stop in the detector.

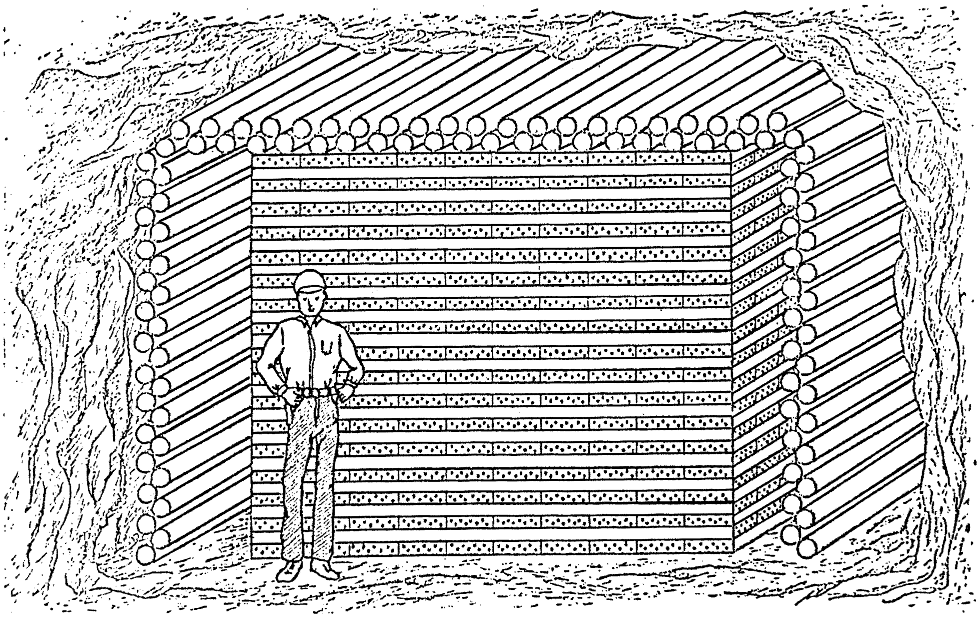

FIGURE 14. The Minnesota experiment on nucleon decay.

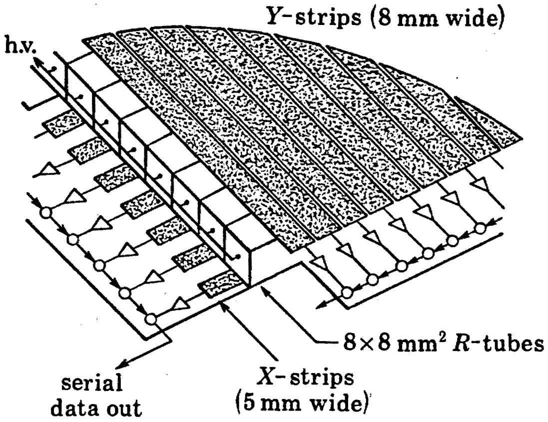

FIGURE 15. The *X*–*Y* readout system of the NUSEX experiment.

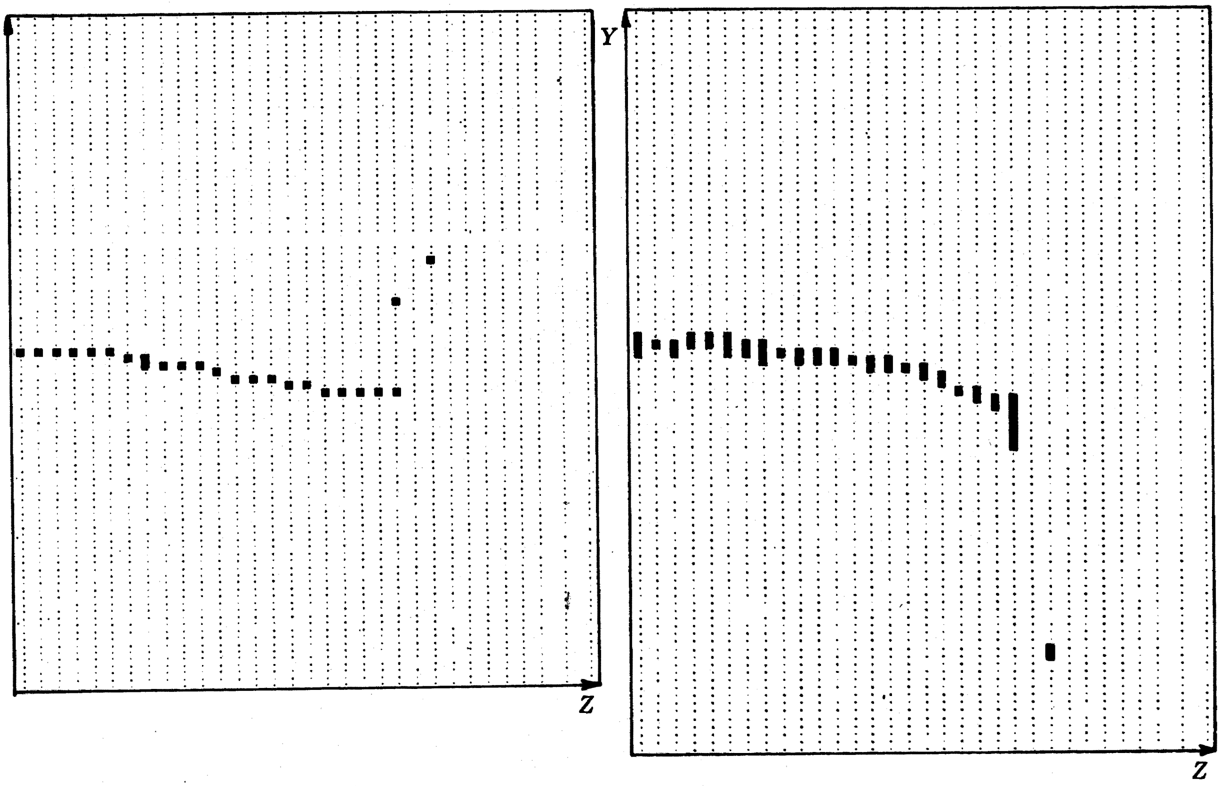

FIGURE 16. A 500 MeV/c pion in the NUSEX apparatus.

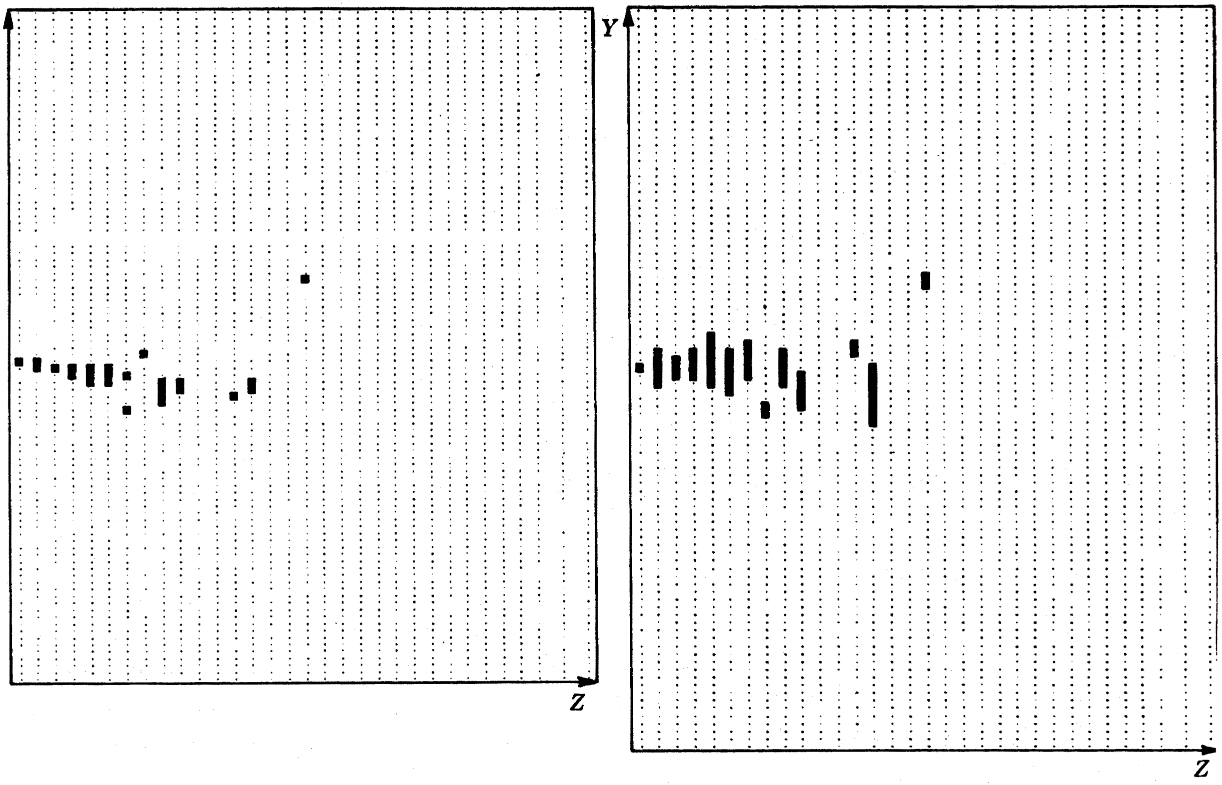

FIGURE 17. A 500 MeV/c electron in the NUSEX apparatus.

To test the system a reduced-scale detector of $3.5 \times 1 \times 1$ 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 figures 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.

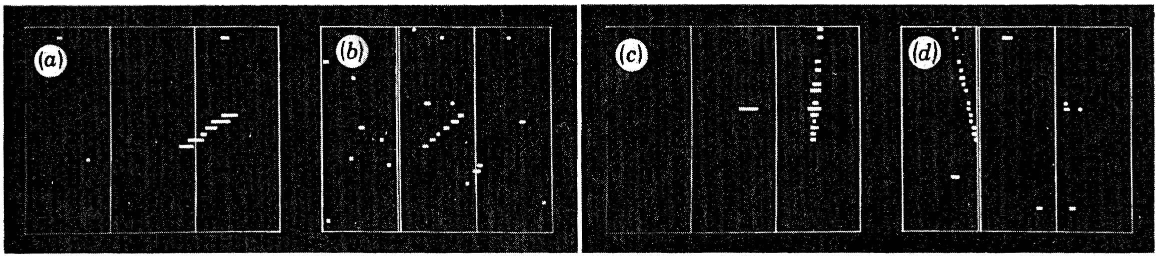

Figure 18. Two-neutrino events in the NUSEX apparatus: (a), (c), top view; (b), (d), side view (rotated 90° clockwise).

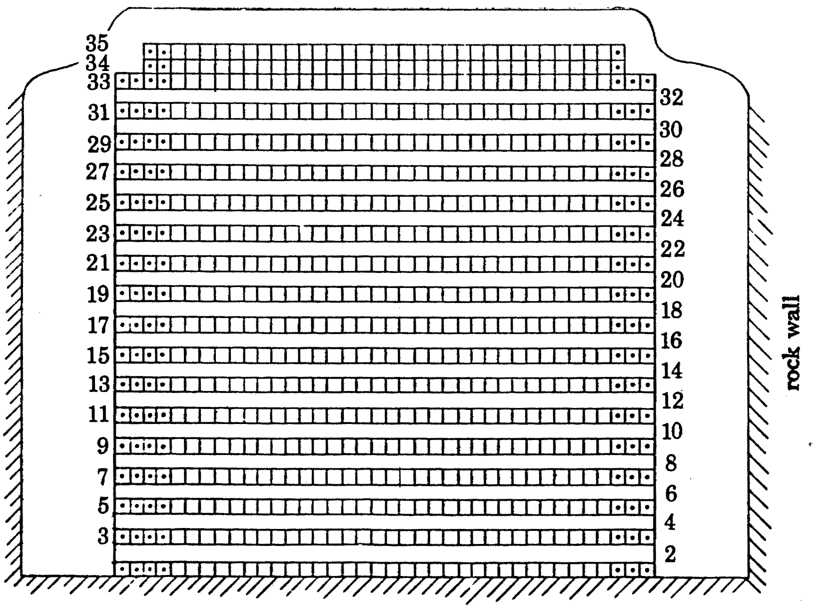

Figure 19. The Kolar Gold Field set-up: front view of proton stability detector.

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 that of atmospheric neutrinos. Until now about 400 neutrino events have been observed with the neutrino beam orthogonal to the iron plates; about the same number are going to be collected at an incident angle of 45°. Some of these events are shown in figure 18.

The only dedicated nucleon decay experiment running at present is that of 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 (figure 19) consists of 34 planes of iron proportional counters of section 10×10 cm^2 and with walls 2.2 mm thick, mounted in alternative layers and interleaved with iron plates 1.3 cm thick.

The total and fiducial masses are 140 and 100 t, respectively. The planes totalling 1600 tubes are operated in fivefold coincidence of any five layers, to avoid spurious counting due to radioactivity (30 and 10 counts per second for the external and internal tubes, respectively). The apparatus has now been operated for 5 months, and 223 muons have been found 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 preceding non-dedicated experiment. One has, however, to point out that none of these events is totally confined in the detector and that, also owing to poor granularity, one has to wait new events and the results of better granularity experiments (like NUSEX) to establish clearly the origin of these undoubtedly interesting events.

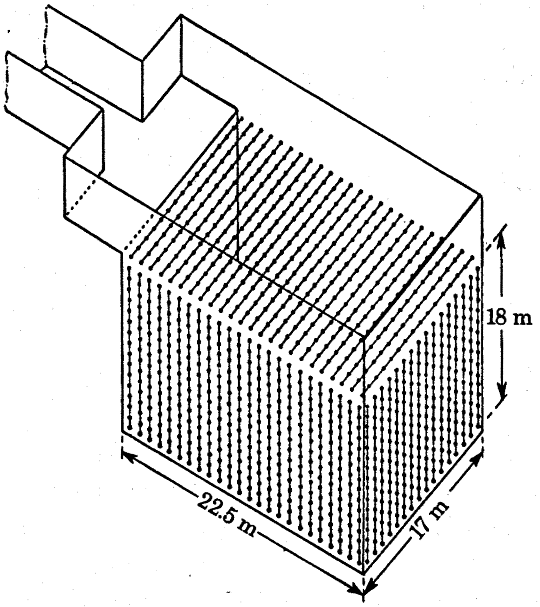

FIGURE 20. The Irvine–Michigan–Brookhaven detector.

5.3. *Experiments based on the Cherenkov light*

Two Cherenkov detectors, in addition to the Homestake set-up already described, are currently being built, both in the U.S.A.

One of them, for the Harvard–Purdue–Wisconsin collaboration, is going to be mounted in the Silver King Mine near Park City, Utah, at about 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, 11.3 m in diameter and 7 m high, containing photomultipliers mounted *inside* (and not on the walls) the active volume about 1 m apart. 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 1 per second. The detector of total mass 760 t 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 Velde 1980; Sinclair 1981) in the Morton Salt Mine (Ohio) at 1670 m.w.e. It consists of a pool of $22.5 \times 17 \times 18\ \mathrm{m}^3$, excavated in the salt and lined with two thick sheets of plastic to be filled with highly purified and continuously filtered water. The Cherenkov light will be detected by means of 2048 photomultipliers (figure 20) immersed in the water near the walls. The time resolution of this experiment (5 ns) should allow the determination of the position of the origin of an event inside the active volume with a precision of about 1 m. 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 decided when the detector becomes operational (at the end of 1981). The final fiducial volume will range between 1600 and 4000 t.

5.4. *Experiments currently being planned*

Various other nucleon decay experiments have been designed and are under consideration by the national funding authorities. A 1.5 kt 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 about 4000 m.w.e. (Bareyre *et al.* 1980). It would consist of a sandwich made by iron plates 3 mm thick interspaced with flash chambers 5.5 mm thick of the type developed by M. Conversi (Conversi & Federici 1978; Ceradini *et al.* 1978; Conversi & 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 magnetostrictive 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 4–6 kt, with limited streamer tubes and flash chambers, to be installed in the Gran Sasso tunnel in central Italy. The French and Italian proposals are strictly connected 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 Cherenkov detector of 14 m side viewed by very large, recently built photomultipliers of 50 cm in diameter. The other, by the KEK–Osaka–Tokio collaboration, consists of the construction of a calorimeter with iron plates 5 mm thick interspaced with planes of flash chambers. The trigger will be provided by 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 1981*a*).

6. EXPERIMENTS ON NUCLEON–ANTINUCLEON OSCILLATIONS

Nucleon–antinucleon oscillations have been suggested by many authors (Kuzmin 1970; Glashow 1979, 1980; Marshak & Mohapatra 1980; Chetyskin 1980; 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 of a mixture of 'pure' neutron and antineutron fields, and n–$\bar{\text{n}}$ oscillations could occur (Baldo Ceolin 1980*a*, *b*; Yoshiki 1980; Green 1981) with a 'free' neutron–antineutron oscillation time

$$\tau_{\mathrm{n}\bar{\mathrm{n}}} = 1/g_{\Delta B=2}, \tag{33}$$

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

$$|\mathrm{n}_1\rangle = \tfrac{1}{\sqrt{2}}\,|\mathrm{n}\rangle + \tfrac{1}{\sqrt{2}}\,|\bar{\mathrm{n}}\rangle, \tag{34}$$

$$|\mathrm{n}_2\rangle = -\tfrac{1}{\sqrt{2}}\,|\bar{\mathrm{n}}\rangle + \tfrac{1}{\sqrt{2}}\,|\mathrm{n}\rangle, \tag{35}$$

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

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

$$|\mathrm{n}_1'\rangle = \cos\theta\,|\mathrm{n}\rangle + \sin\theta\,|\bar{\mathrm{n}}\rangle, \tag{36}$$

$$|\mathrm{n}_2'\rangle = \sin\theta\,|\mathrm{n}\rangle - \cos\theta\,|\bar{\mathrm{n}}\rangle, \tag{37}$$

with

$$\tan\theta = \frac{\Delta m}{\Delta E + [(\Delta E)^2 + (\Delta m)^2]^{\frac{1}{2}}}.$$

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

$$I(\bar{\mathrm{n}}, t) = I(\mathrm{n}, 0)\,\frac{(\Delta m)^2}{(\Delta m)^2 + (\Delta E)^2}\,\{1 - \cos[(\Delta E)^2 + (\Delta m)^2]^{\frac{1}{2}}\,t\}. \tag{38}$$

The main contribution to ΔE, at least in the experiments planned so far, comes from the effect of the Earth's magnetic field on the neutron (antineutron) dipole magnetic moment and is about 6×10^{-16} eV. It is therefore obvious from reaction (38) that the Earth's magnetic field has to be strongly degaussed, for instance by means of a shield of μ metal. From equation (38), moreover, two experimental approaches appear to be possible in principle:

(*a*) Try to keep neutrons under observation for a very long time. In this case the argument of the cosine is very large and reaction (38) becomes

$$I(\bar{\mathrm{n}}, 0) = 0.5\,I(\mathrm{n}, 0)\,(\Delta m/\Delta E)^2. \tag{39}$$

(*b*) Accept a reasonably short observation time. In this case, if ΔE is also small (quasifree neutron condition) equation (38) becomes

$$I(\bar{\mathrm{n}}, 0) \sim I(\mathrm{n}, 0)\,(\Delta m)^2 t^2 = I(\mathrm{n}, 0)\,(t/t_{\mathrm{n}\bar{\mathrm{n}}})^2, \tag{40}$$

and the $\bar{\mathrm{n}}$ impurity does not depend any longer on ΔE.

Experiments on n–$\bar{\mathrm{n}}$ oscillations can in principle be made with three types of neutrons:

(*a*) thermal neutrons with a speed of *ca.* 2000 m s^{-1}, such as those generated by a nuclear reactor;

(*b*) cold neutrons with a speed of *ca.* 200 m s^{-1}, such as those obtained by a passing thermal neutrons through liquid hydrogen;

(*c*) ultracold neutrons with energies *ca.* 10^{-7} eV and a speed of a few metres per second (Golub & Pendlebury 1979).

The only experiment currently in operation is that of the Cern–Grenoble–Padova–Rutherford–Sussex collaboration (Baldo Ceolin 1980*b*; 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 curved guide 9 m long, 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 2×10^9 neutrons per second and an energy spectrum from 10^{-3} to 10^{-4} eV collides with a ^{6}Li target at the end of a long vacuum pipe 3 m (figure 21), where the magnetic field is degaussed by a factor of about 10^{-4} by means of a shield of μ metal.

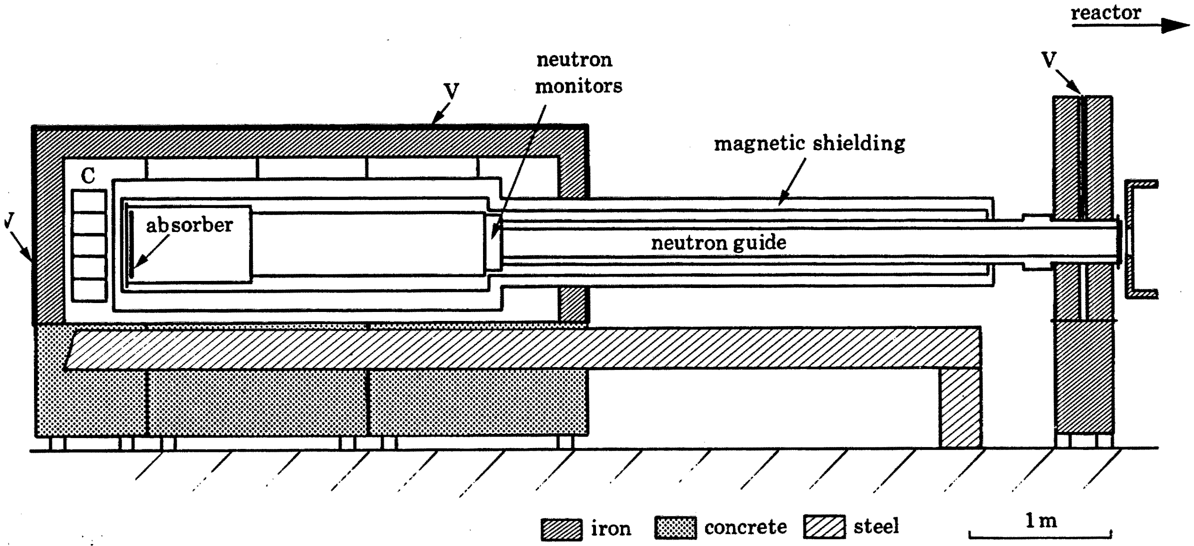

FIGURE 21. The CERN–Padua–Rutherford–Sussex detector for neutron–antineutron oscillations. C, scintillator and lead (calorimeter); V, scintillator (veto counters).

The detector, with a total mass of $\frac{2}{3}$ t is made, at present, by lead plates interspaced with scintillators to reveal the decay products of antineutron annihilation in an energy range between 0.3 and 1.3 GeV. Owing 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 rays, despite a heavy shield of iron, concrete and scintillation counters in a.c. (anticoincidence). The experiment aims to reach the limit of 5×10^6 s for the free nucleon–antinucleon oscillation time, which would correspond to the present limit of *ca.* 10^{30} years from nucleon decay experiments.

Other experiments with thermal neutrons are planned by the Harvard–Oak Ridge, Tennesse 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 (Yoshiki 1980; Baldo Ceolin 1981*b*) owing to their very long wavelength (of up to 100 nm) which prevents them from penetrating 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, reflexion 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 conclude this admittedly incomplete review with the following considerations.

(i) There are for the first time considerable hints that the neutrino mass may be non-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-neutron double β-decay, but none yet for the neutrinoless lepton-violating process. New experiments are planned and it is hoped that they will bring results that will be very relevant to the problem of neutrino mass also. 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 β-decay.

(iv) Various experiments in a wide range of energies and with totally different techniques are being made on neutrino oscillations and should tell us soon if the hints about 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 from three candidates presented by the Kolar Gold Field collaboration. These unusual events have to be found also in the larger and finer-grain detectors currently being built, which should be capable of providing 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, others are not, but very rarely are they as expensive as those with 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 and optics. This is very appealing for an experimentalist: it would be wonderful if the present experimental and theoretical efforts bring not only unification of strong and electroweak forces, but also 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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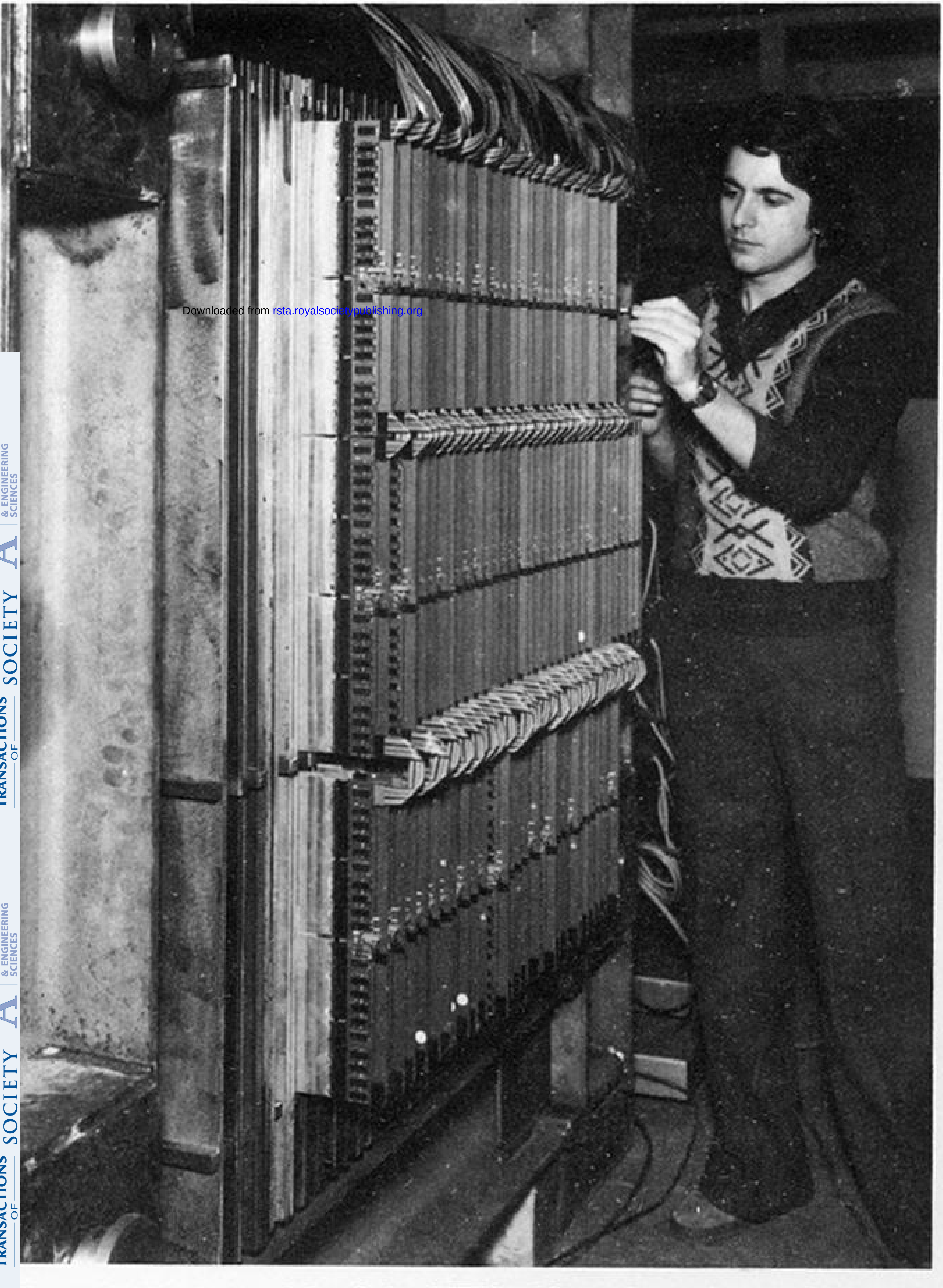

IGURE 12. A model of the NUSEX nucleon decay detector.

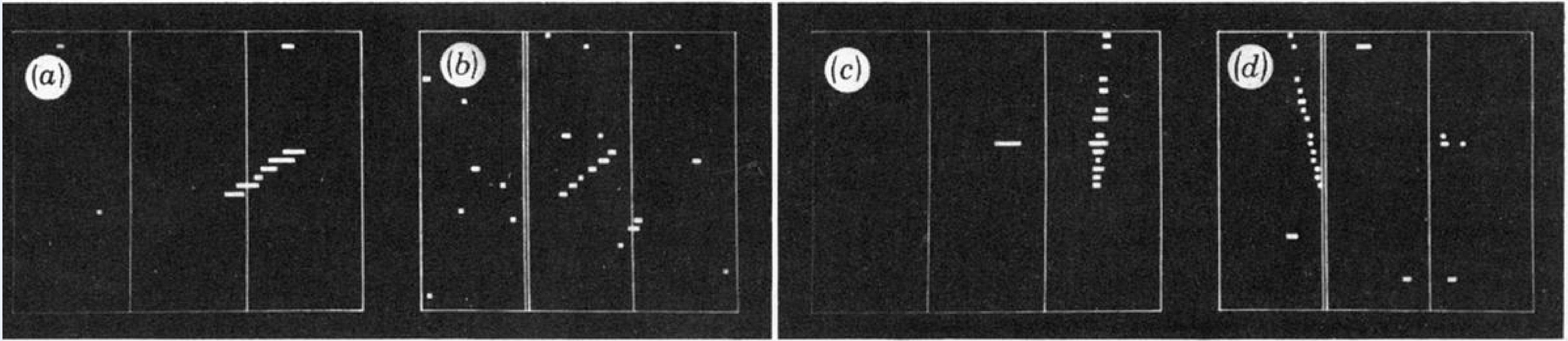

FIGURE 18. Two-neutrino events in the NUSEX apparatus: (*a*), (*c*), top view; (*b*), (*d*), side view (rotated 90° clockwise).