REPORT OF THE WORKING GROUP*

ON

LOW ENERGY AND COSMIC RAY TESTS OF PARTICLE PHYSICS

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Abstract

This report surveys briefly the status of and plans for experiments to search for phenomena "beyond the standard model." Among such phenomena are those suggested and predicted by Grand Unified Theories, particularly minimal SU(5). Emphasis is on the experimental methods and prospects of experiments relating to: proton and bound neutron decay, magnetic monopole searches, neutron-antineutron oscillations, neutrinos and neutrino mass phenomena including double beta-decay and neutrino oscillations, and high energy cosmic rays. A recommendation concerning methods, means, facilities and financial support for such experiments is also discussed.

Introduction

It was the purpose of this Working Group of the DPF Summer Study in Snowmass to study experiments directed at searches for phenomena "beyond the standard model." In our thinking, few limitations were placed on the nature of these exploratory experiments, but emphasis was focused on nonaccelerator experiments since that was the charge to the Working Group.

In our lectures and discussions the close correlation between Grand Unified Theories on the one hand and nonaccelerator experiments on the other hand was displayed again and again. Among other things, it led to a change in name of the Working Group on Nonaccelerator Physics which, in an effort to be more explicit, renamed itself the Working Group on Low Energy and Cosmic Ray Tests of Particle Physics. More importantly, the theoretical perspective provided by Grand Unified Theories[1,2] illuminated the connections among different possible experiments, and aided in the making of value judgements concerning the magnitude of effort and expense appropriate to a given type of experiment.

Thus, the search for a symmetry higher than that of the "standard model," $SU(3)_C \times SU(2)_L \times U(1)$, has led to the simpler group SU(5) from which is obtained the remarkable prediction for the one fundamental constant of the standard theory[3,4]

$$\begin{aligned}(\sin^2\theta_W)_{SU(5)} &= 0.214 + 0.0006 \ln (0.16 \text{ GeV}/\Lambda_{\overline{MS}}) \\ &= 0.214^{+0.004}_{-0.003}\,;\ \Lambda_{\overline{MS}} = 0.16^{+0.10}_{-0.08} \text{ GeV}\end{aligned} \tag{1}$$

that is to be compared with

$$(\sin^2\theta_W)_{Expt} = 0.215 \pm 0.014 \tag{2}$$

the result of precision measurements on semileptonic weak neutral current processes. In eq. (1), $\Lambda_{\overline{MS}}$ is the measured value of the QCD mass scale.[5]

It is a matter of individual taste and temperament as to whether the quantitative agreement between the SU(5) prediction and the data is viewed as a malicious coincidence or the precursor of a new era in physics. However that judgement is made, the meaning of that agreement needs to be explored further, and because its implications are potentially so significant, that exploration should be as systematic and complete as possible.

There are other "natural" consequences of Grand Unified Theories and, in particular, of SU(5). By means of Feynman diagram vertices such as that in Fig. 1, they lead directly to violations of baryon number and total lepton number conservation. These conservation laws are not based on any gauge principle, and the reason for the rigor with which they are upheld in nature has long been a mystery.

There are two phenomena of great interest for which quantitative predictions follow directly from SU(5): (i) the spontaneous decay of protons and bound neutrons, and (ii) the existence of massive magnetic monopoles. These are related through the grand unification mass scale $M_x \approx 10^{14}$–10^{15} GeV.

Thus, in SU(5) the lifetime of the proton and bound neutron is given as

$$\tau_N \approx \text{const } M_x^4/M_N^5 \approx 2 \times 10^{(29 \pm 2)} \text{ yr}, \tag{3}$$

where the ±2 in the exponent is due to uncertainties in $\Lambda_{\overline{MS}}$ and matrix element evaluation.

Again in SU(5), the mass M of the magnetic monopole[6] is of the form

$$M \sim [\alpha(M_x)]^{-1} M_x, \tag{4}$$

where $\alpha(M_x)$ is a known, weak function of M(x). The monopole has a coulombic magnetic field due to its magnetic charge $Q_m = 137e/2$, where e is the electron charge, and behaves as a hadron because it has a screened color field of spatial extent given roughly by $r_c \sim 1/\Lambda_{\overline{MS}}$.

The nucleon mean life and the mass of the monopole are directly related, as indicated in Table I, which suggests that, if SU(5) is valid,

$$10^{16} \lesssim M \lesssim 10^{17} \text{ GeV} \tag{5}$$

Furthermore, there is the capability in SU(5) and other Grand Unified Theories of providing "natural," if not quantitative, explanations of both a baryon asymmetry in the universe and a violation of CP-invariance which has been an enigma for almost two decades.

*This working group consisted of: D. S. Ayres, ANL; D. Caldwell, UCSB; D. Cline, University of Wisconsin-Madison; M. Derrick, ANL; K. Heller, University of Minnesota; R. Holman, NASA; J. Huang, University of Missouri; T. Gaisser, Bartol Research Foundation; L. Jones, University of Michigan; R. Lander, UC-Davis; J. LoSecco, CIT; A. K. Mann, University of Pennsylvania; W. Marciano, BNL; R. E. Shrock, SUNY-Stony Brook; J. Schwarz, CIT; R. Thornton, Tufts University.

At various times E. Loh and P. Sokolsky, University of Utah; V. W. Jones, Louisiana State University; and P. B. Price, UC-Berkeley; also participated in this working group.

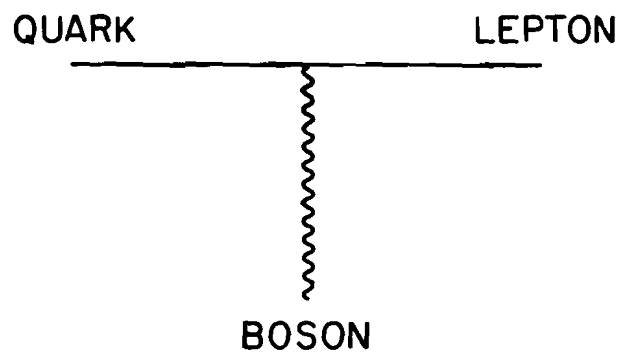

Fig. 1. A possible vertex in grand unified theories; the mass of the boson sets the mass scale of these theories.

Table I. Corresponding numerical values of the nucleon mean life τ_N and the magnetic monopole mass M.

τ_p(yr)	M (GeV)
10^{31}	2.4×10^{16}
10^{33}	7.6×10^{16}

Finally, in the event that minimal SU(5) is inadequate, other phenomena of interest can be accommodated. Among these are neutron-antineutron (n-$\bar{n}$) oscillations, and non-zero neutrino masses which would be manifested in neutrino oscillations and possibly in double beta-decay transitions.

In short, Grand Unified Theories are rich in suggestions and predictions of novel phenomena of great significance which are subject, at least in principle, to experimental test. It was a primary aim of this working group to survey the status of and plans for such test experiments. Nevertheless, we did not restrict ourselves to those experiments alone, but also studied where possible, as in cosmic rays, other experiments that explore "beyond the standard model." Accordingly, the emphasis in what follows is on experimental methods and prospects. In Table II there is a list of the subjects covered and of the individuals in the subgroup that studied a given subject. The salient aspects of most of those studies are presented in this paper, and reference is made to the more exhaustive treatments of them in the papers contributed to these Proceedings by members of the subgroups.

Discussion

Proton and Bound Neutron Decay

The discussion in this section relies heavily on the paper by Ayres et al in these Proceedings and also on the Proceedings of the 1982 Summer Workshop on Proton Decay Experiments at Argonne National Laboratory, June, 1982; the Workshop on Low Energy Tests of High Energy Physics at UCSB, January, 1982; and the Proceedings of the GUD Workshop at the University of Rome, October, 1981.

The present limit of roughly 10^{30} yr on the mean life of protons and bound neutrons is obtained from two experiments[7] carried out with detectors that were ingeniously diverted from cosmic ray studies to the search for nucleon decay. As indicated in Table III, however, there is quantitative disagreement even within SU(5) on the precise values of the branching ratios of possible decay modes. There is also the possibility that the branching ratios in Table III do not correspond to reality at all, and that the dominant decay mode is one for which the detection efficiency of the earliest experiments was low, e.g., $p \rightarrow \bar{\nu} + K^+$, as suggested by some (but not all) supersymmetric grand unified theories.[8] Accordingly, the present limit should be regarded as a relatively loose limit.

The salient properties of "large" mass nucleon decay detectors that have very recently begun to take data or are within about one year of doing so are shown in Table IV. One sees that three of the detectors are very large water Cherenkov counters which are most sensitive to two and three body decay modes. The capability of these detectors for spatial reconstruction is about 70 cm in space and 5 to 10 degrees in angle. They are insensitive to particles with velocities below the threshold for producing Cherenkov light (~100 MeV pion energy), but are calorimeters for showering particles. The Cherenkov light also gives track directionality. Their advantages are relatively low cost for large mass and simplicity of construction, both of which make it possible for them to be early on the scene. Of the two other detectors in Table IV, the one with small mass has just begun to take data while the larger detector has just begun construction. Both of these have relatively small grain size which, within certain limitations, allows for spatial reconstruction and perhaps particle identification for a given event that are superior to those in the large water detectors.

It is interesting to note that, due largely to a topographic accident, the depths at which proton decay experiments can conveniently be located in southern Europe is significantly greater than those generally available in the U.S. or Japan. There is room for debate about the optimum depth necessary for a given detector, but, generally speaking, depths between 2000 and 4000 meters of water equivalent (mwe) (with, if possible, a horizontal adit) seem to be desirable, if not absolutely necessary.

In planning for the future beyond about 1984, there appears to be a consensus that one of three alternative possible results is likely to be forthcoming from the experiments listed in Table IV. These are: (i) that a lower limit to τ_N is found (probably at the level of a few times 10^{31} yr) which is set by the observation of a number of events ("candidates" plus "background"), but not by the total nucleon content of the detectors; (ii) that a clear signal above background is found at a lifetime of a few x 10^{31} yr; and (iii) that zero signal is found at the limit of the total nucleon content of the detectors (but note the decay mode sensitivity of the different detectors mentioned earlier). Under any of these alternatives it is probable that at least one additional multi-kiloton, fine-grained detector will be necessary in the U.S. to provide either a definitive lower limit on τ_N of the order of 10^{33} yr or to study quantitatively the various nucleon decay modes.

The desired properties of that "later" generation detector can be specified even now in a general way. One seeks to measure for all particles (including electromagnetic showers) within the detector: (a) all energy depositions $\gtrsim$ 5 MeV, (b) the x, y, and z positions of the particle (with frequent sampling) with uncertainty $\pm$(1 or 2) mm, (c) the rate of energy loss dE/dz, (d) the total kinetic energy, (e) the range, (f) the sign of the electric charge of decay products or, at least, of $\pi^{\pm}$ and $K^{\pm}$, (g) the time along each particle track, (h) the decay time of muon-decays, and (i) the energy transfers and scattering angles involved in secondary interactions, e.g., of $\pi^{\pm}$ and $K^{\pm}$. Furthermore it is necessary to maximize the redundancy with which each of these quantities is measured. This redundancy is imperative in realizing the aim of reconstructing as fully as possible individual observed events. This latter aim is of primary importance as is indicated by the following numerical example: a mass of 1 metric kiloton contains 6 x 10^{32} nucleons, so that in a detector of fiducial mass 1 metric kiloton with a detection efficiency summed over all possible decay modes of 50 percent, the event rate corresponding to a nucleon mean life of 10^{32} yr would be 3 events/yr. It is unlikely that a definitive conclusion concerning nucleon decay can be reached without full reconstruction of those few events and the background events that will inevitably attend them.

In this connection it is useful to emphasize that the figure of merit F of a nucleon decay detector is not simply its fiducial mass M_{fid} but rather is given by

$$F = M_{fid} \sum_{i}^{n} \varepsilon_i f_i \qquad (6)$$

where ε_i and f_i are the detection efficiency and branching ratio, respectively, of the i th decay mode, and n is the total number of decay modes. Note also that M_{fid} may be a weak function of decay mode.

The numerical example above suggests also that the fiducial mass of any "later generation" detector should be several metric kilotons with the upper limit set by financial and technological restrictions. If the detector construction is modular, it can be produced and brought into operation in stages. An approximate

Table II. Subgroups of and subjects studied by the Working Group on Low Energy and Cosmic Ray Tests of Particle Physics*.

SUBGROUP MEMBERS	SUBJECT
Ayres,† Heller, LoSecco, Mann, Marciano, Shrock, Thornton	1. Summary of Proton Decay Experimental Status/Plans for the Future
Ayres, Cline, Heller, Marciano, Schwarz, Shrock	2. Summary of the Status of Magnetic Monopole Searches
Mann, Shrock	3. Status of n-$\bar{n}$ Oscillation Experiments and Plans
Gaisser, Jones	4. High Energy Cosmic Rays
Holman, Huang, Schwarz	5. Gravitation
Ayres, Caldwell, Gaisser, Lander, Mann, Marciano, Shrock	6. Neutrinos and Neutrino Mass Phenomena Including Double Beta-Decay and Neutrino Oscillations
Ayres, Caldwell, Derrick, Gaisser, Lander, Mann	7. Methods, Means, Facilities, and Financial Support

*Formerly the Nonaccelerator Physics Working Group

†Name of the subgroup leader is underlined

Table III. Predictions for the branching ratios for proton decay in the SU(5) model from P. Langacker, Phys. Rep. 72, 185 (1981). All entries should actually be multiplied by f_p, the fraction of two body decays. Columns sometimes do not add up to unity because of roundoff and the omission of minor modes (including 4% estimated by Din et al. for $\pi^o\pi^o e^+$). The static (NR), recoil (REC), and relativistic (R) models of Kane and Karl are described in the text. A similar table is available for neutron decay.

Mode	M [3.59]	GYOPR [4.47]	D [4.51]	G [4.53]	DGS [4.52]	KK [4.50] NR	KK [4.50] REC	KK [4.50] R
$e^+\pi^o$	33	37	9	13	31	36	40	38
$e^+\rho^o$	17	2	21	20	21	2	7	11
$e^+\eta$	12	7	3	.1	5	7	1.5	0
$e^+\omega$	22	18	56	46	19	21	25	26
$\nu_e^c\pi^+$	9	15	3	5	11	14	16	15
$\nu_e^c\rho^+$	4	1	8	7	8	1.0	2.6	4
μ^+K^o	.3-.5	19	--	7	.5	18	8	5
$\nu_\mu^c K^+$	--	0	--	.5	--	0	.2	.6

Table IV. Properties of "large" mass nucleon decay detectors likely to take data before the end of 1983. (For details of earlier experiments see reference 7.)

GROUP	LOCATION	DEPTH (mwe)	FIDUCIAL MASS(kT)	DETECTOR TYPE
HPW	Park City, Utah Silver Mine	1800	~0.6	Water Cerenkov; PMT in volume and on surface
IMB	Cleveland, Ohio Salt Mine	1570	3.7	Water Cerenkov; PMT on surface
CERN, Frascati, Milano, Torino	Mont Blanc tunnel, Alps	5000	~0.1	Fine-grained; iron plates (1 cm) between streamer counters
Saclay, Wuppertal	Frejus tunnel, Alps	4000	~1	Fine grained; iron plates (0.3 cm) between flash tubes
Tokyo	Kamioka	2400	~1	Water Cerenkov; large area PMT

cost of (5-10) x 10^6 dollars/kiloton of fiducial mass is indicated for such detectors, the more expensive detectors providing more information per event and possessing greater redundancy.

We summarize the expected results from "near" and "far" future detectors and compare them with the present limits on nucleon decay in Fig. 2. Note that the expected results depend on the branching ratios which are (for the moment) very uncertain.

The conclusions to be drawn from the material of this section are as follows:

1. A definitive test of minimal SU(5) will require an empirical limit on the nucleon mean life of $\geq 10^{32}$ yr averaged over many decay modes.

2. Present and soon-to-come experiments searching for nucleon decay do not explore the widest variety of possible decay modes, but will, nevertheless, significantly increase the lower limit on the lifetime, and may successfully observe nucleon decay if the mean life is $\lesssim 10^{32}$ yr.

If the improved limit is reached, a superior, more massive detector will be required to search over a wider range of decay modes at the level of 10^{33} yr.

If nucleon decay is observed, a superior, more massive detector will be required to study quantitatively the various decay modes.

3. A new generation of nucleon decay detectors should be started now (see also the Proceedings of the Summer Workshop on Proton Decay, ANL, June, 1982). These should be fine-grained, tracking detectors with fiducial mass between 1 and 5 metric kilotons. High redundancy, expandability and flexibility of design should be incorporated. Such detectors will probably cost (5 - 10) x 10^6 dollars per kiloton of fiducial mass, and can be realized with present technology.

Massive Magnetic Monopoles

The principal experimental problem in searching for massive magnetic monopoles is that there is no direct relationship between the mass and the velocity of monopoles that can be evaluated quantitatively. Accordingly, one must search over relatively large intervals of mass and velocity, e.g., $10^{10} \lesssim M \lesssim 10^{20}$ GeV and $10^{-5} \lesssim \beta_M \lesssim 0.1$. The energy loss mechanisms for very massive magnetic monopoles are, however, very different in different regions of β_M, and consequently a wide variety of detection techniques must be employed.

Furthermore, astrophysical limits on monopole fluxes depend on both mass and velocity. There are shown in Figs. 3 and 4 plots of the calculated limits on the flux of magnetic monopoles as a function of monopole mass for two values of monopole velocity.[9] The limit referred to as "survival of the Galactic magnetic field" (or Parker's limit) arises from calculations of the maximum flux within our Galaxy that can be tolerated without destroying the Galactic magnetic field, which is presumed to be due to persistent currents; monopoles moving along those field lines would gain kinetic energy at the expense of the field. Figs. 3 and 4 show that the limit based on magnetic field survival becomes less restrictive with increasing mass and increasing velocity because monopoles of larger mass are less easily deflected and monopoles of larger velocity spend less time in regions of coherent field.

The limits in Figs. 3 and 4 referred to as "uniform" and "clumped" arise from consideration of the contribution of the monopole flux to the mass density of the universe and galaxy, respectively. Also shown is the value of the flux inferred from the recent observation of Cabrera.

Fig. 5 is a plot of flux as a function of β_M. This figure and much of the material in this section are from the paper by Cline et al in these Proceedings, which should be consulted for a fuller treatment of the subject. At values of $\beta_M \gtrsim 10^{-3}$ in Fig. 5, flux limits are set by experiments searching for anomalous ionization of nonrelativistic particles. It is more difficult to search in the region $\beta_M \lesssim 10^{-3}$ because the energy loss mechanisms are less well understood there, and no published searches are available in that region. The velocity independent flux inferred from Cabrera's result is also shown.

There are, however, two possibly important interactions of magnetic monopoles with matter that have been discussed recently which would strongly influence the prospects for monopole detection.

(i) It has been suggested by Goebel[10] that the interaction between a magnetic monopole and the magnetic dipole moment of certain nuclei might lead to a bound system; the potential might be of the form $c/(a^2 + r^2)$, where, e.g., $c = -43/2M(^{27}A\ell)$, and a is the nuclear radius. This form is approximate since a detailed calculation is necessary to find the short distance behavior; the long distance form, i.e., $1/r^2$, is well known. The mean length in the earth for the capture of M by $^{27}A\ell$ nuclei, is estimated to be less than 100 km, but even if the capture length were appreciably longer, the effect would still be significant.

(ii) It has been suggested independently by Rubakov[11] and by Callan[12] that (GUT) magnetic monopoles interacting with protons might induce proton decay, e.g.,

$$M + p \to e^+ + M + X \; ; \; X = \pi^o, \pi^{\pm}, \ldots \qquad (7)$$

There is considerable uncertainty at the moment concerning the exact nature of the interaction and therefore of the magnitude of the cross section. If, however, it turns out that the actual cross section is of order the strong interaction cross section, as suggested by Rubakov, rather than of order the weak interaction, then the reaction of eq. (7) would be extremely important, as is indicated by the rough bounds shown in Fig. 5, which are obtained using present limits on proton decay.

It is apparent that detectors designed to search for nucleon decay can also provide a very sensitive search for the reaction of eq. (7). An improvement in the upper bound on proton decay by three orders of magnitude relative to the present upper bound would bring the upper limit on the magnetic monopole flux below the Parker limit (see Figs. 3-5), assuming the cross section for the reaction in eq. (7) is roughly known. If, as seems likely, the cross section were not unduly sensitive to β_M in the interval $10^{-6} \lesssim \beta_M \lesssim 10^{-3}$, the flux limit found in that way would cover a region of β_M that is very difficult to study directly by other means. Note, however, that there is also a bound from observed limits on the x-ray flux from neutron stars[13] which is $F_M \sigma_{\Delta B} \lesssim 5 \times 10^{-49} s^{-1} sr^{-1}$, where $\sigma_{\Delta B}$ is the cross section for monopole-induced nuclear decay.

The proposed methods of searching for GUT magnetic monopoles are numerous and varied; it is not possible to treat them in any detail here. A partial list (given without explanation or references) is the following: (a) SQUIDS, as used by Cabrera; (b) large area ionization and particle velocity detectors, as used to obtain the limits (above $\beta_M = 10^{-3}$) in Fig. 5;

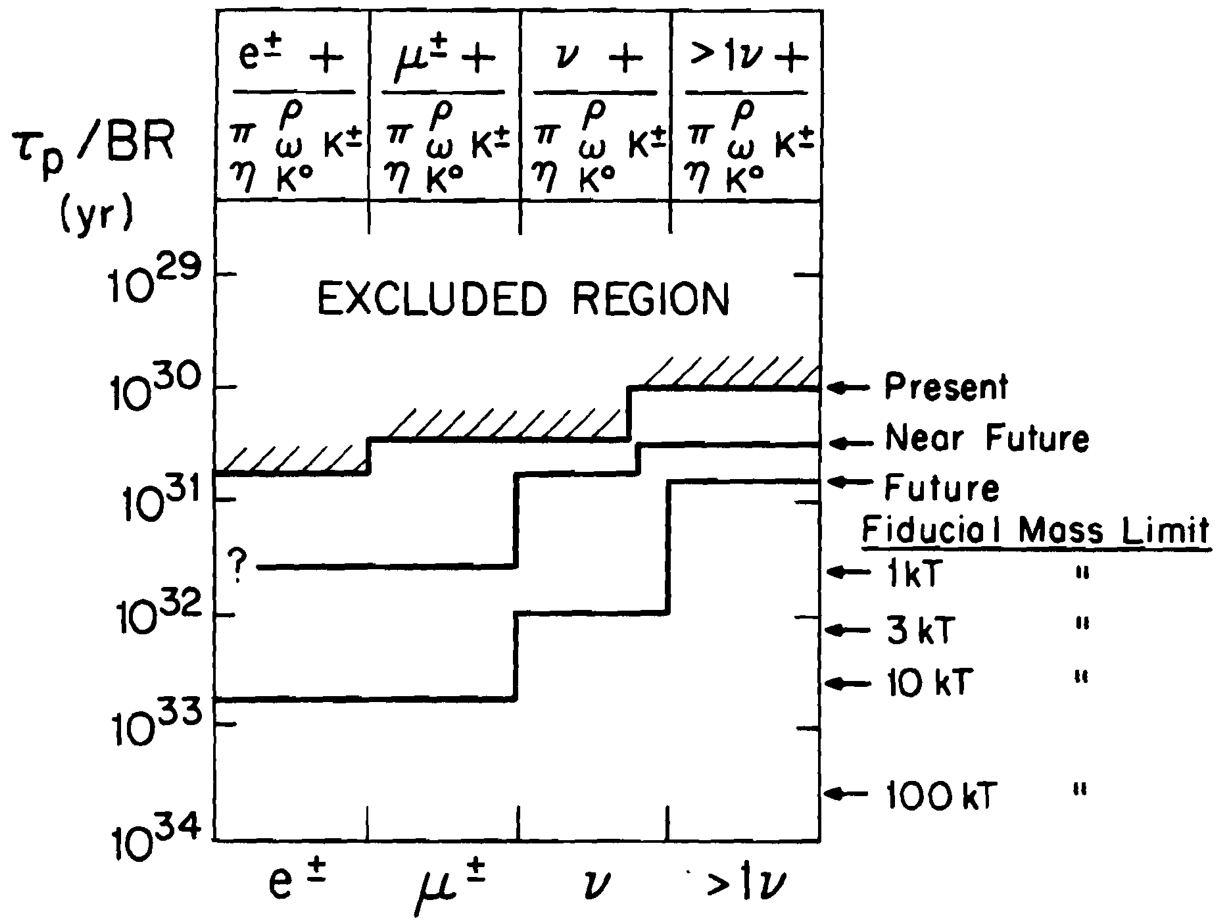

Fig. 2. Approximate expectations for present and future experimental limits on the nucleon lifetime for various decay modes. The limits shown would result from either (1) fewer than five decay events per year or (2) fewer decay events, than neutrino background events, assuming 100% of the decays go into the given channel. Detectors are assumed to have a 33% detection efficiency for decay events, after cuts to remove the neutrino background events. The curve labelled "Present" is for experiments which have been in operation for some time, and are characterized by minimal rejection of the neutrino-induced background (assumed to consist of $\nu_\mu:\nu_e = 2:1$). The curve labelled "Near Future" refers to the expected results from the water Cerenkov experiments and the Frejus tunnel calorimeter. The "Future" curve refers to expectations from fine-grained detectors with $\gtrsim$ 10 kton fiducial mass and 100 times better background rejection for the electron and muon modes than present experiments. The fiducial-mass limits indicated show what could be achieved with a one-year exposure on the basis of the nucleon content of a detector alone. Taken from D. S. Ayres et al., these Proceedings.

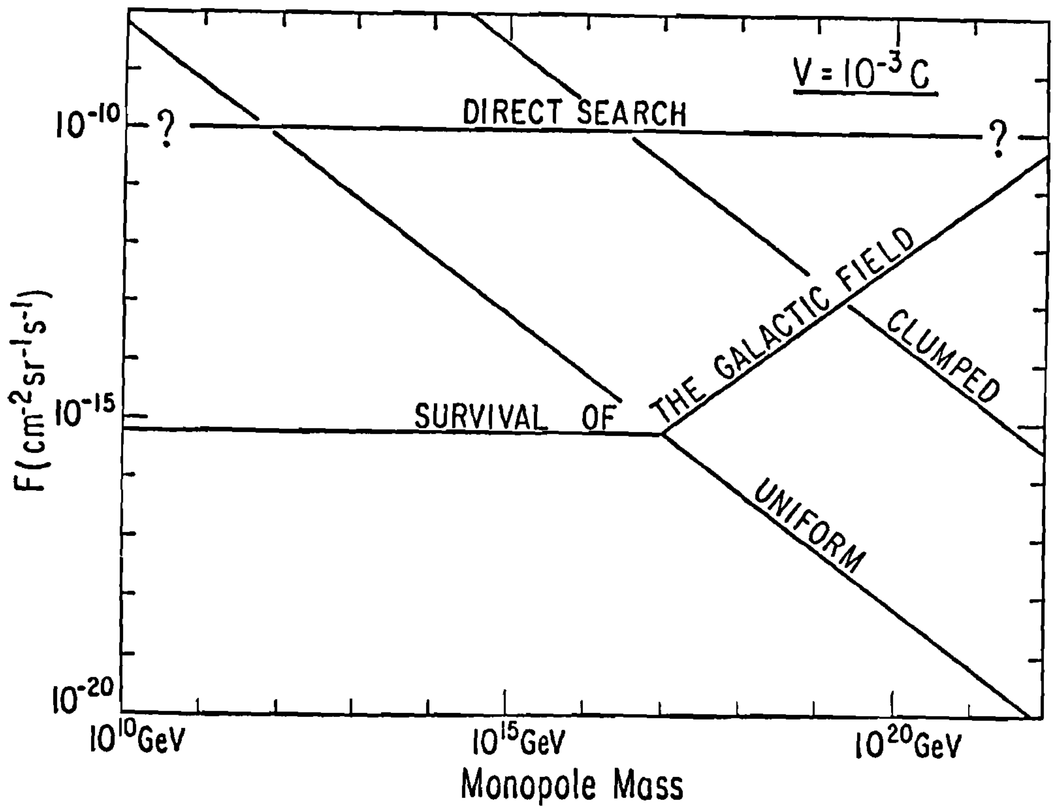

Fig. 3. Reproduced from reference 9. "Summary of monopole flux limits as a function of monopole mass for an initial monopole velocity of $10^{-3}c$, valid for uniform or isotropic velocity distribution. The lines marked 'uniform' and 'clumped' are based upon the mass density of the universe and galaxy, respectively. The 'direct search' limit is based upon refs. 31, 33 and 34 (of reference 9) and is applicable for $2 \times 10^{-2}c \gtrsim 3 \times 10^{-4}c$. However, because of uncertainties with regard to the ionization losses of a slowly-moving monopole,[32] the validity of this bound is in question. The limit based upon the survival of the galactic magnetic field is the flux bound derived in this paper. A monopole mass of $\sim 10^{17}$ GeV separates the two regimes: (i) $v \lesssim v_{mag}$, where monopoles are easily deflected by the magnetic forces; and (ii) $v \gtrsim v_{mag}$, where magnetic force is a small perturbation to the monopole's motion."

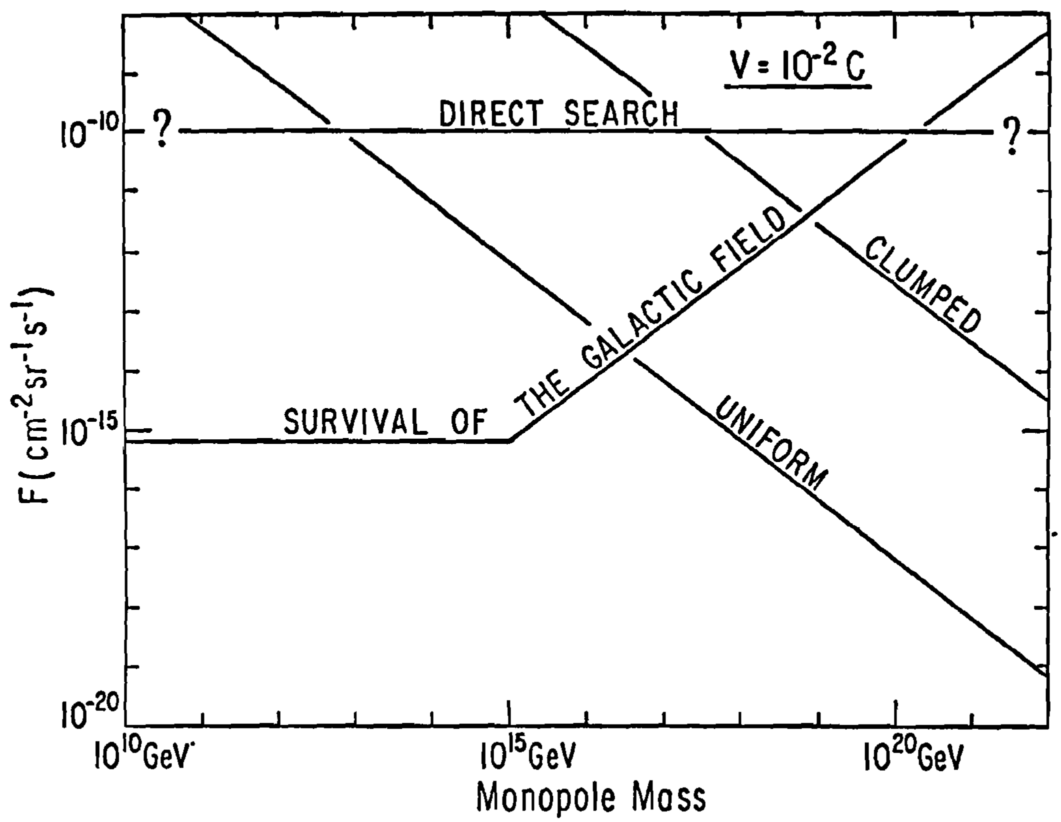

Fig. 4. Reproduced from reference 9. "Same as Fig. 3, except for a monopole velocity of $10^{-2}c$. It is unlikely that monopoles with velocity $v \simeq 10^{-2}c$ could remain clustered with the galaxy since $v_{escape} \simeq 2 \times 10^{-3}c$, however the bound has been included for completeness. The change in the slope of the galactic magnetic field bound for $v \simeq v_{mag}$ occurs for a monopole mass of $\sim 10^{15}$ GeV."

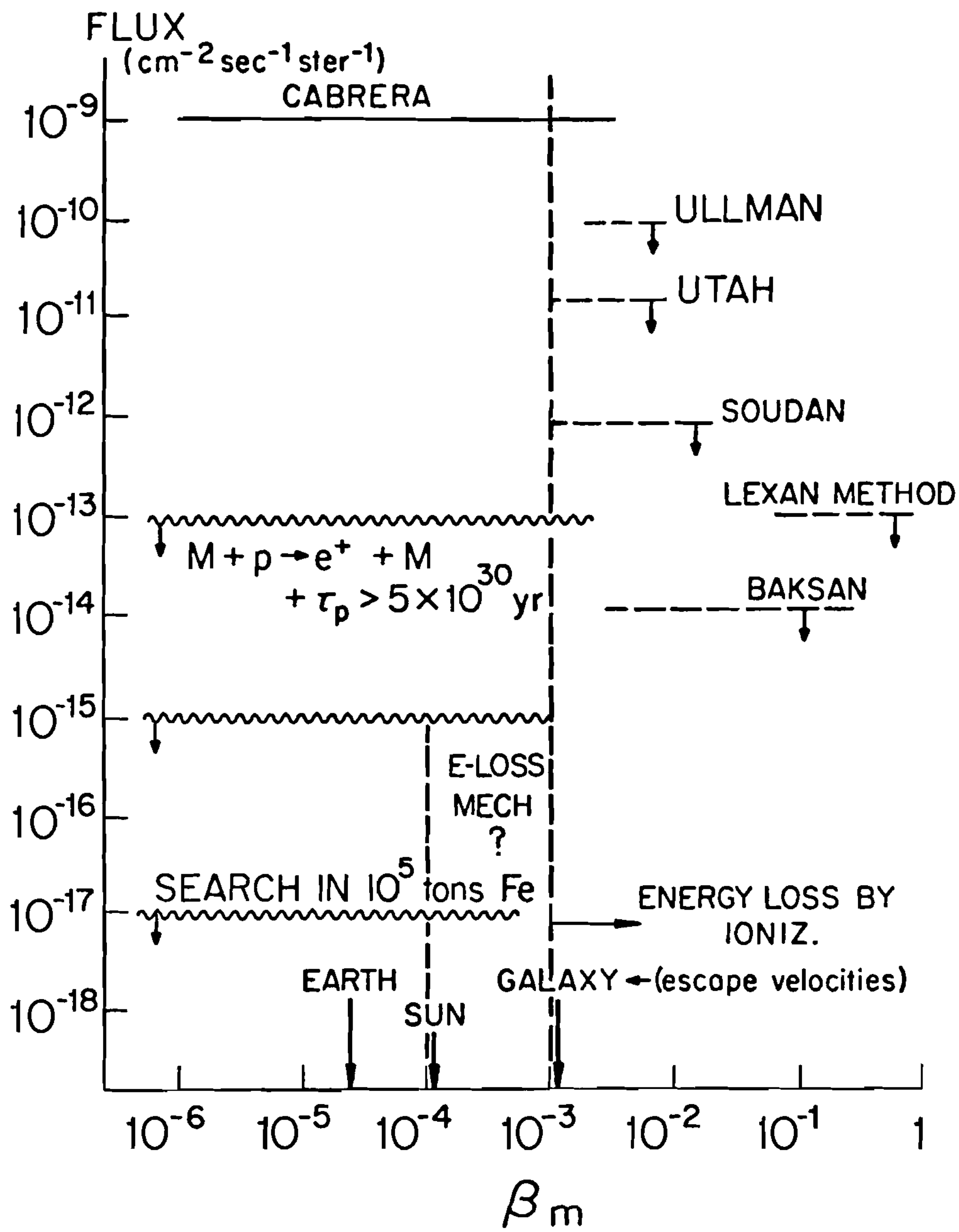

Fig. 5. Graph indicating magnetic monopole flux limits as a function of the monopole velocity. Dashed lines represent limits obtained by ionization measurements. Wavy lines are possible limits that might be obtained from certain searches involving particular assumptions. Also shown is the flux corresponding to the event observed by Cabrera. Taken from D. Cline et al., these Proceedings.

(c) acoustic detectors of induced eddy currents; (d) special materials to detect emitted soft radiation from monopoles; (e) distillation of large quantities of taconite in conjunction with SQUIDS (See Fig. 5); and (f) Zeeman pumping.

We conclude that the hunt for GUT magnetic monopoles, stimulated in part by the result of Cabrera[14], is in full cry. The field is wide open, in both its theoretical and experimental aspects. The next few years promise significant improvements in both areas.

Neutron-Antineutron Oscillations

Neutron-antineutron oscillations[15] require a $|\Delta B| = 2$ transition, which is not allowed in the minimal SU(5) theory. Indeed, suppose the only new mass is of order M_x, then since $\tau_{n\bar{n}} \sim M_x^5/M_N^6$ or

$$\tau_{n\bar{n}} \sim \frac{M_x}{M_N} \tau_p >> \tau_p, \quad (8)$$

the observation of n-$\bar{n}$ oscillations would deny the existence of a particle "desert", i.e., would imply the existence of particles with masses roughly in the TeV region which are implicitly forbidden in minimal SU(5). The observation of n-$\bar{n}$ oscillations would further imply a violation of B-L conservation, also forbidden in the minimal SU(5) theory.

Because it has this capability of discriminating among grand unified theories, n-$\bar{n}$ oscillations are being pursued intensively. A detailed report on the present status of theory and experiment is given by Shrock in these Proceedings.

There are two types of experiments proposed to search for n-$\bar{n}$ oscillations: (i) searches using a beam of free neutrons, and (ii) searches using bound neutrons in ordinary matter.

(i) Among the free neutron experiments are those of Grenoble (in two phases, of which one is complete), Pavia (now in progress), Oak Ridge National Laboratory-Harvard (in late planning stage), and Los Alamos National Laboratory (proposed). The written proposals for these experiments indicate that they should ultimately be capable of exploring most of the interval $10^7 \lesssim \tau_{n\bar{n}} \lesssim 10^8$ sec.

(ii) There are several calculations of the two step process: $n \to \bar{n}$, $\bar{n}$ annihilates on n, which might occur in nuclei. These estimate the total probability per unit time for "matter" decay as the sum of the probabilities per unit time of nucleon decay and the decay of an eigenstate of the n-$\bar{n}$ system. The calculations, which are in relatively good agreement, yield[15] the results given in Table V, which connect the mean life for "matter" decay (the upper bound on nucleon decay taken from experiment) with the mean life of bound neutrons determined by the two step process above.

The correlation between the values of $\tau_{n\bar{n}}$ in Table V and the interval of lifetime accessible to free neutron experiments noted above, on the one hand, and the connection between $\tau_{n\bar{n}}$ and τ_{matter} in Table V on the other hand, suggest that there are two independent experimental methods of searching for n-$\bar{n}$ oscillations with roughly equal ultimate sensitivities. One method is, of course, the free neutron experiments; the other method is to search by means of large nucleon decay detectors for a "decay" process in which approximately 2 GeV is liberated, presumably in the form of pions. It is very likely that both methods will (and should) be pursued vigorously in the next few years.

Neutrinos and Neutrino Mass Phenomena

There is no room in the minimal SU(5) theory for nonzero neutrino masses, but unlike the case of n-$\bar{n}$ oscillations, there are no meaningful quantitative predictions relating to neutrino mass phenomena. There do not exist order of magnitude estimates for either the neutrino mass or the neutrino mixing matrix. Both are required to describe neutrino oscillations[16] since the necessary conditions for oscillations to take place are a nonzero mass of at least one of ν_e, ν_μ, ν_τ, ..., and a violation of separate lepton number conservation, i.e., nonzero mixing angles. For neutrinoless double beta-decay[17], violation of total lepton number conservation is necessary, and either nonzero neutrino mass or the existence of a weak right handed current.

The only positive datum available at the moment[18] is a value $m(\nu_e) \approx 30$ eV, which has been obtained at ITEP from a study of the beta-decay of ^{3}H.

Very briefly, there is at present no convincing evidence for the existence of neutrinoless double beta-decay. However, the fundamental questions of particle physics that are addressed by study of the phenomenon have stimulated experimentalists to plan experiments (of which there are at least seven) that are aimed at increasing the lower limit on the mean life of double beta-decay from about 10^{22} yr to about 10^{24} yr. Data from these experiments, which utilize different parent nuclei and different techniques should be available in the next few years. The situation is described in greater detail in the paper by Caldwell in these Proceedings.

With respect to neutrino oscillations, there are shown in Figs. 6 and 7 the limits on the mass parameters and mixing strengths now available from experiment, and also the limits likely to be forthcoming from experiments in the near future. Fuller discussion of these prospects is given in papers by Lanou and Shrock in these Proceedings.

Figs. 6 and 7 are understood by recognizing that neutrino oscillation experiments fall into two classes: (i) "appearance" experiments in which a search is made for the appearance of a given neutrino flavor in an incident flux which initially did not contain that flavor except possibly as a small contamination (limits in Fig. 6) and (ii) "disappearance" experiments in which a suitably normalized measurement is made of the flavor content of a neutrino beam after it has traversed a given distance to provide a search for the disappearance of a fraction of a given neutrino flavor originally present at zero distance (limits in Fig. 7).

In the latter class, experiments sensitive to small values of Δm^2 are done with $\bar{\nu}_e$ from reactors at the level $\Delta m^2 \gtrsim 10^{-2}$ eV^2 and may be done with ν_e from the sun at the level $\Delta m^2 \gtrsim 10^{-11}$ eV^2. The strength of neutrino mixing that is accessible in such disappearance experiments is of magnitude $\sin^2 2\alpha = 0.1$. It is of interest to note, however, the relatively high upper bound on Δm^2 that has been obtained or is likely to be obtained in the future in experiments at accelerators searching for ν_μ disappearance. Note also the high upper bound on Δm^2 for the oscillation channel $\nu_\mu \leftrightarrows \nu_\tau$ in Fig. 7.

For our purpose here, it is useful to point out that a significant improvement in the upper bound on Δm^2 from a ν_μ disappearance experiment can be achieved in an experiment using cosmic ray neutrinos and a massive detector located underground, similar in kind to those described in the earlier section on Proton and Bound Neutron Decay. A sensitive search for neutrino oscillations involving more flavors than just

Table V. Relation between τ_{matter}^{min} and $\tau_{n\bar{n}}^{min}$.

τ_{matter}^{min} (yr)	$\tau_{n\bar{n}}^{min}$ (sec)
3×10^{30}	2×10^{7}
1×10^{31}	3×10^{7}
1×10^{32}	1×10^{8}
1×10^{33}	3×10^{8}

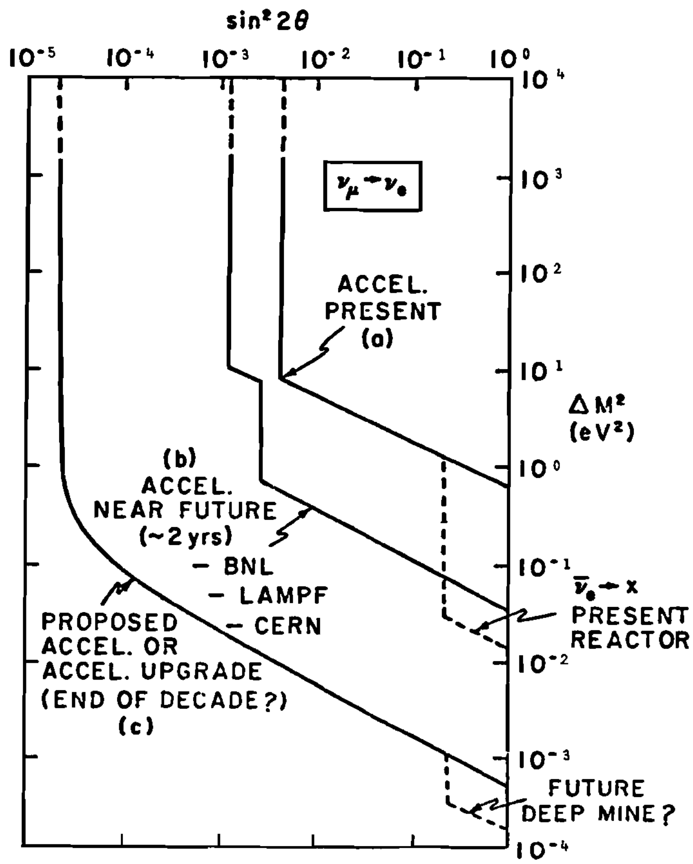

Fig. 6. Summary of neutrino oscillation experiments of the type $\nu_\mu \to \nu_e$, showing (a) the envelope of completed experiments, (b) near future accelerator experiments, and (c) proposed (end of decade) experiments. Reactor experiments are shown for reference. Taken from R. E. Lanou, these Proceedings.

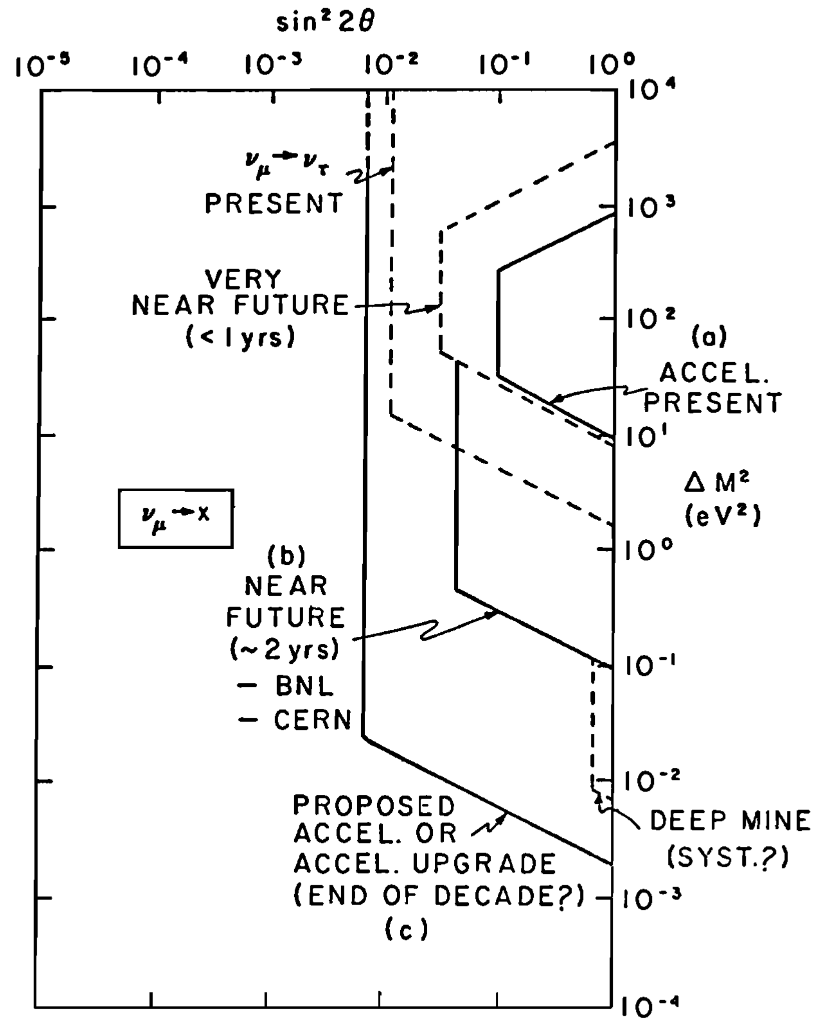

Fig. 7. Summary of neutrino oscillation experiments of the kind $\nu_\mu \to x$, showing present, future, and end of decade experiments. Also included is the result on $\nu_\mu \to \nu_\tau$ and a deep mine experimental result. Taken from R. E. Lanou, these Proceedings.

ν_e and ν_μ is provided by measurement of the ratio of the total number of interactions of upward- and downward-going cosmic ray neutrinos that occur in and are contained in the massive detector. The cosmic ray flux of neutrinos is shown in Fig. 8, and the geometry of the experiment in Fig. 9. Initial measurements will be carried out in the next few years with the generation of detectors aimed principally at searching for proton decay.

The experiment has the following advantages: (1) it is the only experiment that is capable of searching for the disappearance of ν_μ and $\bar{\nu}_\mu$ at the limiting value $\Delta m^2 \lesssim 10^{-4}$ eV^2; (2) because it measures the quantities $N_{tot}(up)$ and $N_{tot}(dn)$ the experiment is relatively insensitive to systematic errors; (3) the experiment is capable of observing time averaged probabilities $\langle P_{e\tau}\rangle_t$ and $\langle P_{\mu\tau}\rangle_t$ of magnitude set by mixing strengths corresponding to, e.g., the d- to s-quark mixing strength; (4) although the experiment relies on the upward-going neutrinos traversing a substantial fraction of the earth's diameter, its sensitivity is not limited by matter-induced oscillations. The principal disadvantage of the experiment is that it requires a very massive (~10 kiloton) detector in which the neutrino interactions must occur and be contained; the detector must also be well enough instrumented to distinguish clearly upward-going from downward-going neutrinos. To obtain sufficient statistical precision, the data-taking period must be at least one year.

A detailed description of the nature and possible outcomes of the experiment is given in a paper by Ayres, Gaisser, Mann and Shrock in these Proceedings.

High Energy Cosmic Rays[19]

It is useful to ask what information arises in the study of high energy cosmic rays that is significant for particle physics, and, in particular, for grand unified and astrophysical theories. This question is addressed by a four part answer in a paper by Gaisser and Jones in these Proceedings.

1. Particle interactions at very high center of mass energies.

At present, cosmic ray data yield a total cross section for proton-proton scattering of (60-70) mb in the center of mass energy interval (1-2) TeV, which fits satisfactorily on a smooth curve extrapolated from present accelerator data, and suggests that no appreciable surprise awaits us in p-p total cross section measurements at proton-proton colliding beam machines in the next few years.

A major goal of the Fly's Eye experiment (which is described in these proceedings by Cady, Cassiday, Elbert, Loh, Sokolsky, Stech and Ye) is to extend the p-p total cross section measurement to $\sqrt{s} \sim 100$ TeV, more than an order of magnitude beyond accelerator energies of the next decade. Cosmic ray determinations of the cross section and other global features of hadronic interactions are exploratory in nature, searching for major new features up to the highest energies possible.

2. High energy interactions between nuclei.

Around 1-1000 TeV it is possible to use cosmic ray nuclei to study nucleus-nucleus collisions. Again, this energy range will be well beyond that accessible with heavy ion accelerators for some time. The JACEE experiment, described in these Proceedings by W. V. Jones et al., is an example of such an experiment, one goal of which is to search for possible new states associated with a phase transition to quark-gluon matter.

3. High energy astrophysics and cosmology.

Here the subject matter is essentially in areas of astrophysics, some of which have potentially significant implications for the connection between cosmology and grand unified theories. Two of the subjects at which much experimental effort is directed are: (i) the energy dependence of the chemical composition of primary cosmic rays, and (ii) the shape of the primary energy spectrum, particularly around 10^{15}-10^{16} eV and above 10^{19} eV. Since interpretation of the atmospheric cascades at these energies depends on calculations based in large part on models of hadronic interactions, these studies can be thought of as "applied" particle physics. They bear on the origin, acceleration and propagation of cosmic rays and include the possibility of distinguishing primordial ($Z \lesssim 2$) from processed ($Z > 2$) cosmic ray nuclei above 10^{15} eV. In turn it is hoped that observations at such energies might identify extragalactic components, if any, of cosmic rays and look for a cutoff above 10^{20} eV due to collisions on the microwave background.

4. Antimatter searches and baryon asymmetry.

There is convincing evidence that our Galaxy consists only of baryons, and there is additional evidence that on the scale of clusters of galaxies matter and antimatter (if it exists at all as the material of galaxies) are unmixed. A baryon asymmetry of the universe may have a natural explanation in grand unified theories, but is not yet supported by experimental data on the larger scale of the universe. Direct evidence of distant, large-scale regions of antimatter might come from cosmic rays with $Z < (-1)$, which are unlikely to be the result of cosmic ray collisions with ordinary matter. An experiment to search for anti-Fe/Fe at the level of 10^{-7} (about two orders of magnitude lower than the present limit on anti-He/He) has been proposed[20], which, it is argued, would be sufficient to see extragalactic cosmic ray antimatter (if any) flowing into our Galaxy.

Summary

The mass scale of 10^{14} to 10^{15} GeV represented by the diquarks and leptoquarks of grand unified theories and the phenomena that follow therefrom are challenges to the current experimental methods of particle physics. On the one hand, energies related to that mass scale are not accessible to present or contemplated particle accelerators. On the other hand, experiments capable of searching for the predicted very rare, low energy particle decays and interactions that are essentially relics of the "hot big bang" may just be feasible with present experimental techniques.

Apart from the calculated value of the interaction strength of the electroweak theory, the sharpest single quantitative prediction is that of the mean life of protons and bound neutrons. The value obtained is achievable by some present and planned detectors in the kiloton mass region able to provide sufficient information content per observed event to discriminate against cosmic ray neutrino-induced background and to allow full reconstruction of events that are candidates for nucleon decay. Such detectors should be able to reach a mean life value of 10^{33} yr. To go beyond 10^{33} yr is very difficult.

There are, as we have seen, additional experiments of appreciable interest that can also be done with a detector of the mass and quality necessary to obtain a conclusive result on nuclear decay at the most sensitive

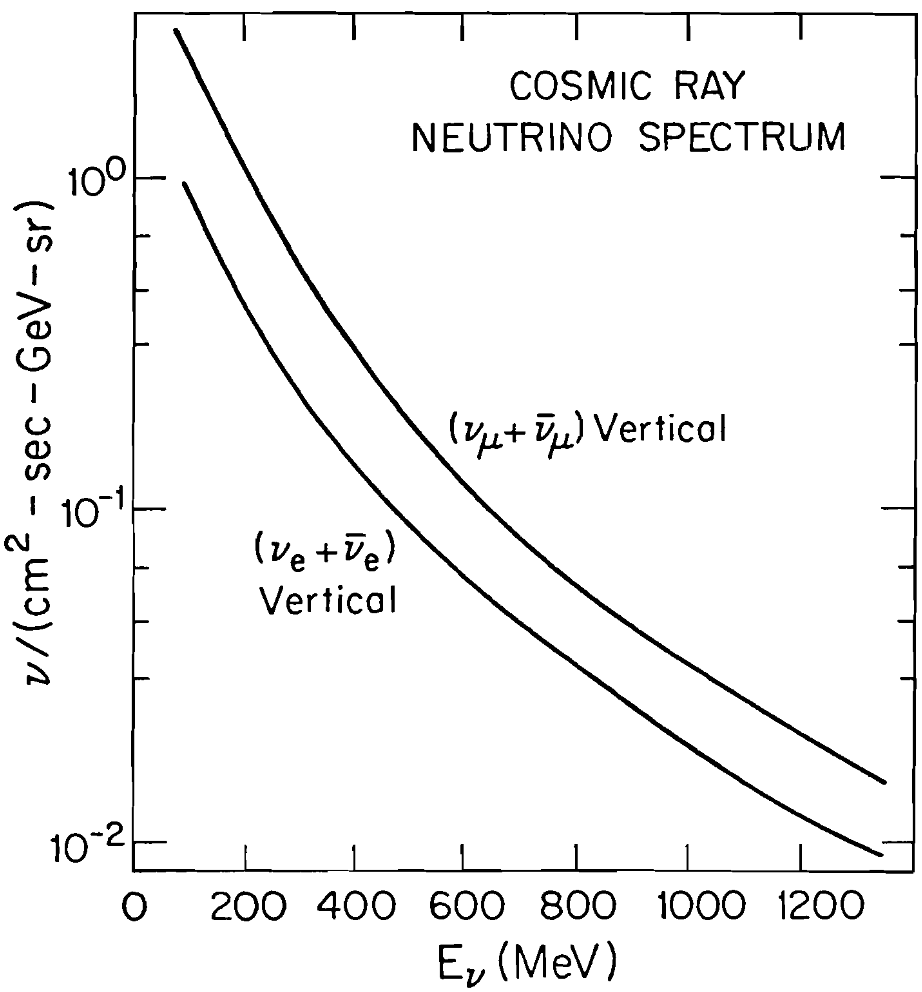

Fig. 8. Calculated cosmic ray neutrino spectra. See Reference 4 in paper entitled Neutrino Oscillation Search with Cosmic Ray Neutrinos, by Ayres, Gaisser, Mann and Shrock, these Proceedings.

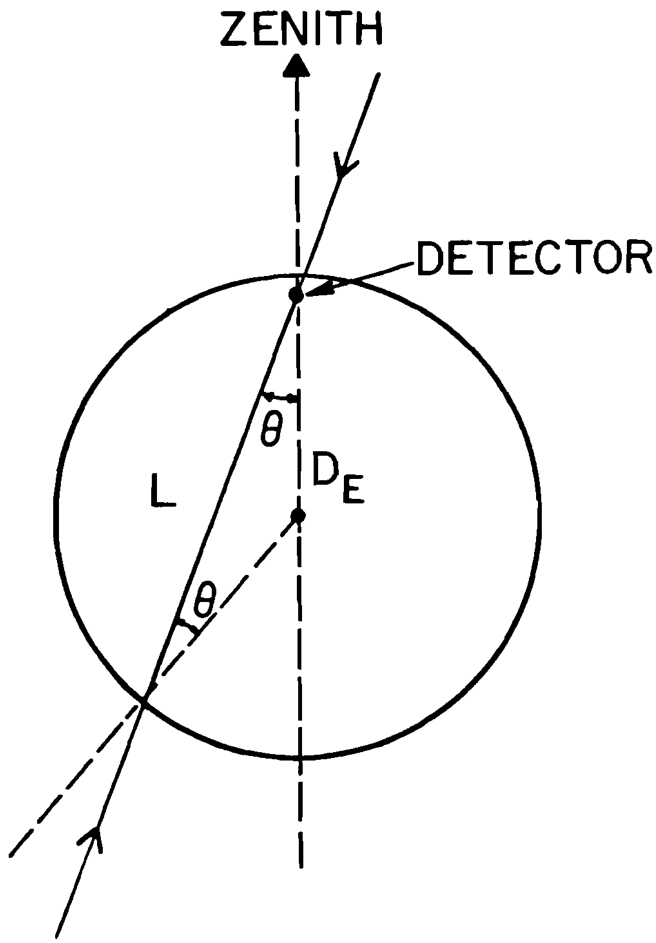

Fig. 9. Sketch of the experimental method. The neutrino detector is located as indicated roughly 1-2 km below the earth's surface. Neutrinos originate in the 10-20 km thick atmospheric shell surrounding the earth. Neutrinos from near the zenith that intersect little of the earth's matter before interacting in the detector are called down-going, N(dn). Neutrinos that have traversed a large fraction of the earth's diameter ($D_E = 1.3 \times 10^7$m) and are observed to produce upward-going interactions in the detector are called up-going, N(up). Present accelerator limits on neutrino oscillations suggest that oscillations should have a negligible effect on the down-going atmospheric neutrino flux.

level. Among these are searches for GUT magnetic monopoles and for n-$\bar{n}$ oscillations. Furthermore, in such a detector, a detailed study of the cosmic ray neutrino flux and a search for other astrophysical sources of neutrinos can be made, leading in turn to a ν_μ disappearance type neutrino oscillation experiment capable of searching in a region of Δm^2 approximately 10^3 times lower than any accelerator experiment of that type. Still other experiments are possible with more specialized detectors that might be applied to the problem of nucleon decay and also to the detection in real time of solar neutrino interactions.

Finally, improved beta-decay and double beta-decay experiments are in progress to search for the effects of a nonzero neutrino mass and violation of lepton number conservation. And studies of the constituents of primary cosmic rays at very high energies may probe the flow of matter into our galaxy and the question of the baryon asymmetry of the universe.

All of these experiments constitute important tests of fundamental aspects of grand unified theories and of the cosmological model that is so closely related to them. If the experiments can be carried out to definitive conclusions - positive or negative - they may provide entry to a new area of physics or indicate that such entry is unavailable, at least by present experimental methods.

References

1 H. Georgi and S. Glashow, Phys. Rev. Lett. 32, 438 (1974).

2 P. Langacker, Phys. Rep. 72, 185 (1981).

3 H. Georgi, H. Quinn and S. Weinberg, Phys. Rev. Lett. 33, 457 (1974).

4 W. Marciano and A. Sirlin, Phys. Rev. Lett. 46, 163 (1981).

5 A. Buras, Proc. of the 1981 Lepton-Photon Symposium.

6 D. P. Dokos and T. N. Tamaras, Phys. Rev. D 21, 2940 (1980); M. Daniel, G. Lazarides and Q. Shafi, Nucl. Phys. B 170, 156 (1980).

7 M. L. Cherry et al., Phys. Rev. Lett. 47, 1507 (1981); M. R. Krishnaswamy et al., Phys. Lett. 106B, 339 (1981).

8 S. Dimopoulos, S. Raby and F. Wilczek, Phys. Lett. 112B, 133 (1982); J. Ellis, D. Nanopoulos and S. Rudaz, CERN preprint 3199 (1981).

9 These plots are from Michael S. Turner, E. N. Parker and T. J. Bogdan, EFI Preprint No. 92-18.

10 C. Goebel, private communication.

11 V. Rubakov, JETP Lett. 33, 644 (1981).

12 C. G. Callan, Jr., Phys. Rev. D 25, 2141 (1982); see also F. Wilczek, Phys. Rev. Lett. 48, 1146 (1982).

13 E. W. Kolb, S. A. Colgate and J. A. Harvey, LA-UR-82-1963; submitted to Phys. Rev. Lett.

14 B. Cabrera, Phys. Rev. Lett. 48, 1378 (1982).

15 See the review by R. N. Mohapatra, preprint CCNY-HEP-82/7, May, 1982.

16 For reviews, see, e.g., A. K. Mann and H. Primakoff, Phys. Rev. D 15, 655 (1977); S. M. Bilenky and B. Pontecorvo, Phys. Rep. 41, 225 (1978).

17 For a review, see H. Primakoff and S. P. Rosen, Ann. Rev. Nucl. Part. Sci. 31, 145 (1981).

18 V. A. Lubimov et al., Phys. Lett 94B, 266 (1980).

19 For a review of cosmic rays in conncetion with particle physics, see T. K. Gaisser and G. B. Yodh, Ann. Rev. Nucl. Part. Sci. 30, 475 (1980) and T. K. Gaisser, Comments Nucl. Part. Phys. 11, 25 (1982).

20 S. B. Ahlen, P. B. Price, M. H. Salamon and G. Tarle, Ap. J. 260, 20 (1982) and N.I.M. 197, 485 (1982). See also "Searches for exotic particles" by P. B. Price in these Proceedings.

Appendix on Experimental Evaluation, Facilities and Financial Support

The development of grand unified theories in conjunction with the "hot big bang" cosmology and the need to test them as exhaustively as possible is stimulating a multiplicity of experiments of great complexity and difficulty. These experiments, using the most advanced techniques of physics, begin to rival in cost, manpower, and potential significance the most ambitious particle physics experiments in major accelerator laboratories. Accordingly, the Working Group on Low Energy and Cosmic Ray Tests of Particle Physics discussed at length the problems associated with the emergence of this area of experimentation. The results of these discussions are embodied in the document that follows.

LOW ENERGY AND COSMIC RAY TESTS OF PARTICLE PHYSICS Experiment Evaluation, Facilities and Financial Support

Introduction

Although the physics of elementary particles has in the main been studied using accelerated beams of particles in a well-controlled laboratory environment, there have usually been important experiments that have utilized other techniques. For example, in the decade following the Second World War, cosmic radiation provided a competitive source of high energy particles and several fundamental particles were discovered by this means.

In more recent decades, there has been a concentration of resources, far beyond those available earlier, in major accelerator facilities. This, plus the establishment of an organizational framework that encourages wide participation of the particle physics community in experiments, has in part led to a revolution in our understanding of nature. During this period, the relative contribution of nonaccelerator experiments has declined.

Today, as a result of conceptual advances connected with gauge theories and the precise data accumulated by the accelerator experiments, the "standard model" discussed elsewhere in these Proceedings has developed. The next decade or so of accelerator experiments will be largely devoted to working out the consequences of this model.

The standard model does not pretend to be the ultimate model of the universe, and there are a number of grand unified theories (GUT) that incorporate the standard model as a low energy approximation. In simplest versions of these GUT models, there is no new physics between center of mass energies of a few hundred GeV and 10^{14} GeV, the region between being designated as a desert. Other versions of GUT lead to predictions that perhaps can be tested with accelerators of higher energy than now exist, some of which are currently under construction.

These GUT models, however, also lead to testable predictions that reflect the influence of the extremely high energy mass scale of 10^{14} GeV which is inaccessible to accelerators. Among these predictions are the decays of nucleons (baryon number non-conservation), the existence of massive magnetic monopoles, lepton number non-conservation, non-zero neutrino masses and the possibility of spontaneous neutron-antineutron oscillations.

We may therefore be in a situation where investigation of the frontier of particle physics beyond the standard model will depend as much on nonaccelerator experiments and experiments at lower energy, high intensity facilities (including reactors) as on experimentation at the highest energy accelerators. It is, therefore, useful to review the methods, facilities, and financial support employed in carrying out these "low energy and cosmic ray tests" of particle physics.

Comparison of Methods in Accelerator and Nonaccelerator Physics

Over the years, efficient mechanisms have grown up for carrying out experiments at the accelerator laboratories. Much of the funding is placed at the disposal of the director of the facility to be used in support of the experiments chosen by the director with the advice of a program committee. The funding agencies are responsive to these selections, and channel additional funds directly to the universities engaged in the selected experiments.

The situation in nonaccelerator experiments is quite different. There is a greater diversity of experiments and approaches, and many of the experiments are small in size and scope. Although the HEP offices at DOE and NSF are receptive to good scientific proposals, there is a significant asymmetry in the way proposals for support of accelerator and nonaccelerator experiments are handled. In general, there is less opportunity for nonaccelerator experimental proposals to be exposed to detailed presentation to a peer group or an evaluation by a technical advisory staff. Even if support is received, such experiments do not generally have access to engineering and technical help to large scale computing facilities, and to other support facilities comparable to those at the accelerator laboratories. For a large nonaccelerator experiment, the review of costs and engineering feasibility that usually precedes an approval at an accelerator laboratory cannot be carried out in the same detailed way as is normal with an accelerator experiment. Nor, if costs escalate during the construction, is there a resource pool that can soon be made available. Furthermore, the large accelerator laboratories with their major continuing programs inevitably have first call on the funds available, and so a much smaller pool is available to the nonaccelerator experiments.

The relative importance of these factors varies with the size of the experiment: smaller activities may benefit from the absence of additional bureaucracy, but the larger activities would certainly be helped by easier access to large scale engineering and technical support facilities that could be utilized as needed. The nucleon decay experiments, which begin to approach major accelerator experiments in scale, as well as the proposed n-n̄ and neutrino oscillation searches, constitute experiments of considerable cost and sophistication.

Recommendation

To evaluate the large nucleon decay experiments, DOE set up an *ad hoc* Technical Assessment Panel which concluded its deliberations early in 1982. *As an initial step toward a more efficient consideration of proposals, we suggest that a committee with larger purview be formed to provide advice on nonaccelerator experiments in general.** For this committee to be useful, it should have a wide range of expertise. It should also have access to a technical staff and be fully aware of the financial resources available for this work. In almost all cases, financial constraints clarify the decision making. The committee would advise the agencies about funding priorities, with full knowledge of the whole range of nonaccelerator experiments. The committee would represent this area of physics to the general physics community, and might also stimulate the organization of workshops and other methods of long range planning for the nonaccelerator experiments.

Exactly which activities should come before this committee needs to be carefully considered. For example, the high energy cosmic ray work has as much overlap with astrophysics as with particle physics, and so might not be appropriate for such a committee.

It would be hoped that the committee would not place impediments in the way of physicists who wish to set up small experiments financed out of their normal, continuing funds. It could, however, act as a catalyst in encouraging new small activities to get started, and in making such opportunities known to the scientific community.

Long Range Possibilities

As we have discussed, lack of centralized support provides some problems to the nonaccelerator experiments, although at present, the situation does not seem to be critical. If nonaccelerator experimentation expands, then some more efficient mechanism for providing technical and other support to this field of particle physics should be set up. Some obvious suggestions are (1) to ask one of the DOE laboratories that does not act as an HEP accelerator center to take on this role; (2) to ask the three HEP accelerator laboratories to share this responsibility; (3) to consider setting up a new organization that could be linked to an existing laboratory. A National Underground Science Facility has been discussed in this context.

There is no obvious way of deciding these issues at this time. It is, however, important to further discussion in the community, and this Summer Study has provided one such valuable opportunity. We note that results will soon be available from the new nucleon decay detectors. A known nucleon lifetime or a confirmed magnetic monopole flux, with implications for other predictions of GUT theories, would have a clarifying effect on our thinking about these questions.

Summary

There are certain experiments suggested by GUT or, more generally, by the search for higher symmetries in nature, that may have special importance. These experiments form a loosely defined area that may be called "Low Energy and Cosmic Ray Tests of Particle Physics." Some of the experiments are approaching in complexity and cost the major experiments at high energy accelerator laboratories. The diversity of the area and its relative newness make it difficult to evaluate and support individual experiments in a way that would generally improve their efficiency and productivity.

To alleviate this difficulty, we suggest that a committee, advisory to the funding agencies, be formed to assess proposals for such experiments and recommend the level of financial and other support for them. This committee would replace a number of ad hoc committees and provide more orderly and scientific procedures in the administration of this area of physics research. It would also represent this area of physics to the supporting agencies and to the general physics community. While its scope may be difficult to define with precision initially, we are of the opinion that time and custom will lead to reasonable and beneficient boundaries. As this field grows, it may be desirable to establish a funding channel for nonaccelerator physics similar to that which now exists for national laboratory accelerator physics.

*This has already taken place.

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