NONACCELERATOR PHYSICS WORKING GROUP SUMMARY

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Summary

The Nonaccelerator Physics Working Group set itself the task of predicting the contributions of nonaccelerator experiments to particle physics during the 1990's, in order to assess the needs for new experimental facilities. The main topics studied by the subgroups were: (1) the possibility of doing particle physics experiments with high energy cosmic rays from astrophysical sources; (2) the prospects for experiments which seek to measure the masses of neutrinos and the mixing of neutrino flavors; (3) an examination of the implications for proton decay of recent theoretical developments in grand unified and string theories. Other topics included a survey of magnetic monopole searches, an assessment of future prospects for double-beta-decay and nucleon-decay experiments, and a review of recent progress on neutrino and dark-matter detectors based on quasiparticles in superconductors and phonons in crystals.

Introduction

Particle physics in the 1990's will attempt to explore phenomena beyond those predicted by the standard model, to expose manifestations of the fundamental physics which must underlie it. While the SSC will be the primary tool of this quest, nonaccelerator particle physics experiments can provide much complementary information on the same fundamental questions, and also offer an opportunity to study particle physics beyond the TeV energy regime of the SSC. The goals of the Nonaccelerator Physics Working Group were to predict the contribution of nonaccelerator experiments to the study of particle physics in the 1990's, and to assess the needs for new experimental facilities. The substantial overlap of the physics goals, the underlying theory, and the instrumentation needs of SSC and nonaccelerator physics experiments has lead to a corresponding overlap among the physicists working in these areas. Snowmass 86 has provided an excellent opportunity to exploit these common interests of the participants.

Three subgroups were established to focus on areas of particular interest in nonaccelerator physics: the Cosmic Ray Subgroup was led by Mike Cherry, the Neutrino Subgroup by Gene Beier, and the Proton Decay Subgroup by Bill Marciano. The working group was also able to establish useful contacts with the participants of three other workshops which were being held concurrently. The interactions with the Aspen Astrophysics Workshop led to interesting discussions of the early universe, dark matter, and sources of high energy cosmic rays, which are reported in these proceedings. Participants in the Aspen Workshop on String and Superstring Theory contributed substantially to the Proton Decay Subgroup, and participants in the Lewes Workshop on the Early Universe described recent developments in particle detectors based on quasiparticles in superconductors and on phonons in crystals. These ideas may lead to powerful new detectors for double beta decay experiments, solar neutrino detection, and dark matter searches.

Summary of the Cosmic Ray Subgroup

High Energy Cosmic Ray Sources

Cosmic ray air shower detectors[1] are currently operating in the United States at Dugway, Los Alamos, and Homestake. At Dugway, the Fly's Eye, using two different modes of operation, detects atmospheric scintillation and Cerenkov light from 10^{14} eV up to the highest cosmic ray energies of 10^{20} eV. In addition, the Eye is currently being augmented by two large counter arrays for electron and muon identification. An electron array with a central muon detector and very good directional response has recently been implemented at Los Alamos for energies above 10^{14} eV. At Homestake, an air shower array ($E > 3 \times 10^{14}$ eV) and Cerenkov mirror are currently operating in conjunction with the deep underground detector. TeV gamma ray studies are being carried out in this country with Cerenkov telescopes at Dugway, Mt. Hopkins, and Haleakala.

Much of the recent cosmic ray interest has concentrated on identification of sources -- in particular high energy emission from binary x-ray sources. There have been conclusive identifications of several sources by the Fly's Eye, Cerenkov mirrors, and air shower arrays, and it appears in fact that most if not all binary x-ray sources are also intense sources of high energy radiation.[2] Cygnus X-3 is an example of a neutron star in close orbit around a larger companion. (Grindlay[3] has suggested that there may be a third object in the system as well.) It is one of the brightest x-ray sources in the Galaxy; it is a highly variable source of radio emission, sometimes flaring in intensity by as much as three orders of magnitude in the space of one or two days (and repeating this spectacular behavior typically once a year); it is a sporadic and unpredictable "on-again-off-again" emitter of TeV gamma rays; and it has been seen by the Kiel and Haverah Park air shower arrays at energies up to 10^{16} eV.[4]

The radiation reaching the earth from Cygnus X-3 must be neutral: it propagates in a straight line through 11 kpc or more of interstellar magnetic field. The radiation also maintains the 4.8 hr phasing imposed by the neutron star's orbital period (except for the radio, which originates not from the neutron star but from a surrounding nebula). Neutral 10^{16} eV secondaries are presumably produced by 10^{17} eV primaries accelerated at the neutron star. Although cosmic rays have been observed at energies up to 10^{20} eV, these have been thought to have been accelerated in a series of sequential steps over a long time rather than in an initial impulse. Cygnus X-3 affords us our only example of such enormous energies being produced in a single discrete accelerator. This one source could be responsible for a major portion of the Galaxy's total cosmic ray output at energies of 10^{15} eV and above.[2]

Underground observations of Cygnus X-3 have been controversial. The Soudan[5] and NUSEX[6] groups have reported observations of high energy underground muons with the characteristic 4.8 hr period from the direction of Cygnus X-3; but the larger IMB, HPW,

Homestake, Frejus, Baksan, and Kamioka detectors have seen no positive effects. The results are summarized in these proceedings.[4] Given the poor statistics of the initial Soudan and NUSEX results and the lack of confirmation, there is good reason to question the existence of a long-term underground Cygnus X-3 effect. However, the Soudan group have recently stirred the pot by presenting an extremely interesting suggestion of a high energy underground signal around the time of the very large radio burst in October 1985.[7]

If these results are confirmed (and even if they are not),[8] a new generation of cosmic ray detectors must have the capability of studying particle physics at cosmic ray energies in much more convincing detail than has been possible heretofore. The cosmic-ray detector group at Snowmass 86 has suggested how one might go about constructing a muon spectrometer for high and low energy muons, together with an electron array for simultaneously studying the electromagnetic shower component.[9]

Magnetic Monopoles

The status of large (> 1 m^2) superconducting monopole detectors was described by Gustafson (Chicago-Fermilab-Michigan) and Cabrera (Stanford).[10] Their results, together with the IBM, Imperial College, and NBS results, already set an upper limit below 10^{-12} monopoles $cm^{-2}sec^{-1}sr^{-1}$, which is only slightly above the Parker bound at the Planck mass.

In order to reach the mass-independent Parker bound of 10^{-15} $cm^{-2}sec^{-1}sr^{-1}$, an area of roughly 100 m^2 will be required. Although there is hope of building such immense superconducting arrays in the future, the only detector of comparable size currently operating is the large (128 m^2) liquid scintillation detector which has just begun looking for monopoles in the Homestake Mine. Although this detector has been operating in a muon mode since 1985, the monopole electronics have only recently been installed. Construction of the MACRO detector, a 1200 m^2 combined scintillation-streamer tube-track etch detector in the Gran Sasso tunnel, is scheduled to begin in April 1987.

It had been suggested that scintillation detectors might have an intrinsic lower velocity threshold[11] at $6 \times 10^{-4}c$. At this meeting, Musser[10,12] presented new results from tests in a BNL neutron beam showing detectable light levels at proton velocities of $2 \times 10^{-4}c$. As a result, both the Homestake and MACRO detectors can expect to probe the Parker limit for monopole velocities above about $10^{-4}c$; they will be limited by radioactivity background and not by light levels or slow monopole energy losses.

Dark Matter, WIMP's, and Cosmic Neutrinos

If photinos or other weakly interacting massive particles (WIMP's) are the dark matter that closes the universe, then it was pointed out by Gaisser[13] that the neutrino-induced event rate in nucleon decay detectors can be calculated for WIMP's of various masses annihilating in the sun. In particular, 3 - 15 GeV photinos are already ruled out by the neutrino rate seen in the IMB detector.

Auriemma,[14] on the other hand, suggests that the 15 eV ultraviolet emission seen by the IUE satellite may be explained by a cosmic background of 30 eV neutrinos or light photinos, and further claims that the muon-rich "gamma ray" events seen by the Kiel air shower group from Cygnus X-3 can be explained by a suitably large gluino flux. He calculates the photon and gluino fluxes produced in pp collisions, takes into account the gamma ray absorption by the microwave background, and suggests that the Cygnus X-3 gluino flux may exceed the photon flux near 10^{15} eV.

Stenger[15] too, notes the 10^{15} eV gamma ray attenuation by the 3° background radiation, and finds that if the neutrino and gamma ray fluxes are comparable at the source, then the observed (unattenuated) high energy neutrino flux could be as much as 50 times the photon flux at the earth. This leads to the suggestion that it may be possible to detect point sources of cosmic neutrinos with 10^3 - 10^4 m^2 underground or underwater neutrino detectors (i.e., DUMAND or MACRO).

Summary of the Neutrino Subgroup

Perspective

Neutrino physics was born with the postulated existence of the particle by Pauli and quantified with the four fermion interaction proposed by Fermi, both in the 1930's. Two decades later, the neutrino played a fundamental role in developing an understanding of parity violation and the V-A interaction. In 1959 the neutrinos were observed to interact for the first time by Cowan and Reines. The quantitative experimental studies of neutrino properties and interactions was initiated with the first accelerator neutrino experiment in the early 1960's, in an experiment which demonstrated that neutrinos exist with distinct flavors. This experiment initiated a quarter century of activity, leading to an understanding of the nature of the electroweak interaction and the use of neutrinos as a probe of the structure of hadronic matter. In 1986 we find that accelerator neutrino physics is reaching a natural conclusion, with experiments which extend the precision of existing measurements the principal unfinished business for the accelerators.

In spite of the progress of recent years, the study of neutrinos is still fundamentally incomplete: the masses, flavor mixing, and number of flavors are yet to be determined. The question of the number of flavors of light neutrinos is likely to be settled with precise measurement of the width of the Z boson at the colliders within a few years, but the remaining problems of neutrino mass and flavor mixing are most likely to be addressed through nonaccelerator experiments in the coming decade. For this reason the Neutrino Subgroup at Snowmass 86 focused on three principal topics directed toward the understanding of neutrino mass and mixing: direct measurements of neutrino mass, double beta decay, and the sun as a source of neutrinos.

There is no fundamental principle which constrains neutrino masses to be zero as there is with the photon, the only other fundamental particle which is lighter than the electron. On the other hand, the mass of the electron anti-neutrino is certainly small, less than 50 eV. There are two ways in which effective interactions which generate neutrino mass can be constructed. Dirac mass terms conserve the total lepton number, L, but the mechanisms which generate the masses of the other Dirac particles, the charged leptons and the quarks, do not easily produce small neutrino masses. Majorana neutrinos are self conjugate (neutrinos and anti-neutrinos are the same particle). The effective interaction which generates a Majorana mass violates the conservation of total lepton number by two units, but allows neutrino masses

which are very different from the masses of quarks and charged leptons. The knowledge that the masses of the neutrinos are small leads to some prejudice that the neutrinos are Majorana particles.[16]

Direct Measurement of Neutrino Mass

Twelve active or proposed experiments address the problem of neutrino mass directly by making precision measurements of the spectrum of electron energy near the endpoint of the reaction

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e .$$

A review of the status of these experiments was presented to the workshop by O. Fackler.[17] These experiments are difficult, requiring good resolution, high luminosity, and small background for good sensitivity. Furthermore, the experimenters must either understand the atomic and molecular final state interaction effects, or they must design an experiment which excludes effects from final state interactions.

Five experiments have presented results to date. These results are summarized in Table 1. The Moscow-ITEP experimenters have responded to critical analyses of their procedures, and still report a non-zero result for the mass of the electron anti-neutrino. The Zurich group result is almost in conflict with the Moscow result. The Zurich result has a large background, and many studies have been made of the systematic errors which this background might produce. The conclusion reached at this workshop is that the new experiments are beginning to produce results, and we expect the Moscow-ITEP result to be confirmed or refuted soon. Looking toward the future, experiments now under construction or taking data may have a sensitivity of 2-5 eV. Speculations on the ultimate sensitivity to neutrino mass of the tritium beta decay endpoint experiments leads to about one half electron volt, but with substantial investment.

Table 1

Summary of Results of Tritium Endpoint Measurements

Group	Signal Events	Background Events	Result
Zurich	690K	1200K	$m_\nu < 18$ eV
Moscow-ITEP	130K	-	$17 < m_\nu < 40$ eV
Beijing	30K	-	$m_\nu < 30$ eV
Tokyo-INS	5K	-	$m_\nu < 33$ eV
Los Alamos	400	small	$m_\nu < 30$ eV

Double Beta Decay

The process by which certain nuclei decay to other nuclei with the emission of two electrons and possible additional particles is called double beta decay. The present status and future prospects of this very active field were reviewed at the workshop by D.O. Caldwell.[18] In this summary we limit the discussion to neutrinoless double beta decay:

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

This process violates lepton number by two units. If the process is mediated by neutrino exchange, as most models for calculating the rate would suggest, the neutrino is necessarily a Majorana neutrino. Furthermore, as shown by Kayser,[19] observation of neutrinoless double beta decay would imply a significant lower limit on the mass of one flavor of neutrino.

Experiments on neutrinoless double beta decay may use the same material for both the source and the detector, as in ^{76}Ge or ^{136}Xe experiments, or use thin strips of source material surrounded by detector, as in the current generation of ^{100}Mo experiments. The best results achieved to date use ^{76}Ge as the source. The results can be expressed as upper limits on the effective mass of the intermediate neutrino. Assuming the absence of right handed currents for the neutrino interaction, no CP violation, and allowing for some uncertainty in the calculation of the relevant nuclear matrix elements, the neutrinoless double beta decay experiments imply upper limits on the effective neutrino mass of a few electron volts. This limit is not in conflict with a direct measurement of neutrino mass in the range of 20-30 eV. Rather, if a measurement of neutrinoless double beta decay observes a rate corresponding to a certain effective mass, the measurement implies that some neutrino mass is greater than the experimental effective mass.[19]

Present experiments are limited by the number of source nuclei and by background. To make substantial progress, future work in this field must address these limitations. In the immediate future, Soviet physicists plan to utilize 10 kilograms of isotopically pure ^{136}Xe and 15 kilograms of isotopically pure ^{76}Ge. (The natural abundances of these isotopes used in existing detectors is slightly less than ten percent.) It is estimated that the future Soviet experiments could extend the lifetime limits for ^{136}Xe by 10^3 and for ^{76}Ge by 20 over the best current limits. Hope for further improvement rests on technological developments. Detector possibilities discussed by D.O. Caldwell[18] and B. Cabrera, et al.[20] using techniques of condensed matter physics could lead to substantial improvements in resolution and background rejection. A specific example is 0.3 kilograms of superconducting, isotopically pure ^{100}Mo, which could lead to the same lifetime limit as the Soviet experiments in one year. The resolution is expected to be good enough that the experiment would not be background limited, and the lifetime limit would improve directly proportional to the running time rather than as the square root of the running time as in background limited cases.

The Solar Neutrino Opportunity

Substantial discussion of new experiments to detect solar neutrinos and the interpretation of the possible outcomes of these experiments was an important activity of this workshop. The result of this activity is the Report of the Working Group on Solar Neutrinos in these proceedings.[21] The interest in solar neutrinos results from the discrepancy of a factor of three between the only measurement of solar neutrinos and the expectation of the best calculations, known as the standard solar model. This discrepancy has stood for many years, with many people believing that it was a consequence of inadequate modeling of the sun or of incorrect input to the model, such as nuclear physics cross sections. Today, the nuclear physics questions have been largely laid to rest. The discrepancy is now generally believed to

require modification of the standard solar model by which the expected flux of neutrinos is generated, or to require better understanding of the properties of neutrinos. In the latter case, the properties of the neutrinos could cause the flux of neutrinos detected by the existing experiment to be different from the flux of neutrinos produced by the sun.

The particle physics mechanisms invoked to explain the solar neutrino puzzle, as the discrepancy is known, are neutrino oscill' tions, neutrino magnetic moments which precess in the solar magnetic field, and neutrino decay.[21] All of these mechanisms, when introduced into the solar neutrino puzzle, were unnatural in that they required the properties of neutrinos to be tuned to particular values to agree with experiment. The recent observation[22] that solar matter could enhance the effect of vacuum oscillations for a large range of mass and mixing parameters is much more natural than the conventional particle physics mechanisms, and even includes mass and mixing parameters which are encompassed by theoretical prejudice. Thus the study of solar neutrinos may be a unique opportunity to study fundamental properties of elementary particles. An agressive experimental program could resolve the solar neutrino puzzle within the coming decade.

Proton Decay Subgroup Summary

The proton decay subgroup focused its attention on the status of proton decay from both theoretical and experimental perspectives. Expectations for the dominant decay modes in various theoretical scenarios were reviewed[23] and compared with up-to-date experimental bounds.[24] Predictions and limits for baryon number violation via magnetic monopole catalysis[25] and n-$\bar{n}$ oscillations[26] were also examined. Ongoing proton decay experiments, detector upgrades and future plans were discussed. A study of the ultimate proton lifetime limits attainable with an earth based detector was undertaken.[27] Conclusions reached regarding those topics are summarized below.

Theoretical Motivation

The belief that baryon number violating interactions exist and that protons should ultimately decay is well founded in cosmology and elementary particle theory. The observed baryon-antibaryon asymmetry of the universe naturally suggests baryon number violation during the early evolution of our universe. Whatever interaction was responsible for that asymmetry should still be present in nature, albeit as a super-weak effect. In the case of theory, GUTS (grand unified theories[28]) generically predict proton decay via super-heavy gauge bosons and Higgs scalars. Unfortunately, the expected decay rate is very uncertain. GUTS also predict the existence of magnetic monopoles which can catalyze proton decay[29] and, in some specific Higgs symmetry breaking mechanisms, the possibility of n-$\bar{n}$ oscillations.[30] Either of these occurrences would be readily observable in the large underground detectors specifically designed to search for proton decays.

The most closely scrutinized proton decay mechanism is via super-heavy vector bosons. In GUTS, such decays can be mediated either by $X^{\pm\,4/3}$, $Y^{\pm\,1/3}$ or $X'^{\pm\,2/3}$, $Y'^{\pm\,1/3}$ gauge bosons. The predicted proton lifetime (or baryon number violating neutron lifetime) is approximately bounded by[23]

$$\tau_p \lesssim 6 \times 10^{32}\ (m_X/10^{15}\mathrm{GeV})^4\ \mathrm{yr}$$

with $p \to e^+\pi^0$ and $n \to e^+\pi^-$ the dominant decay modes. The $p \to e^+\pi^0$ decay signature is particularly clean for water Cerenkov detectors, because it is easily distinguished from neutrino backgrounds. Unfortunately, the sensitive dependence of τ_p on m_X implies that at best one can search up to $m_X \simeq 3 \times 10^{15}$GeV with future detectors before being overwhelmed by neutrino backgrounds which become dominant at the 10^{34} yr level. If we are lucky, proton decay will reveal itself before that occurs.

Scalar bosons can also mediate proton decay. One finds that if such scalars have mass m_H, they lead (very roughly) to predicted lifetimes[23]

$$\tau_p \simeq 8 \times 10^{29}\ (m_H/10^{11}\mathrm{GeV})^4\ \mathrm{yr}$$

with $p \to \bar{\nu}_\mu K^+$ and $n \to \bar{\nu}_\mu K^0$ the dominant decay modes ($p \to \mu^+K^0$ and $n \to \mu^+\pi^-$ are also quite significant). For such events, the tracking calorimeter detectors are particularly well suited for distinguishing proton decay from neutrino backgrounds. In this case, future experiments may probe up to $m_H \simeq 10^{12}$ GeV. That type of intermediate mass scale may occur in some local supersymmetry models.

In some supersymmetry scenarios, dimension 5 operators can also induce proton decay via loop effects.[23,31] Generally, if such operators are present, the decays $p \to \bar{\nu}_\tau K^+$ and $n \to \bar{\nu}_\tau K^0$ are expected to dominate; however, in superstring theories, the couplings and dominant decay modes from dimension 5 operators and scalar mediated decays are not well specified. Those types of decay mechanisms are the only ones likely to be observed in superstring scenarios, since the gauge boson mass m_X is expected to be very large $\simeq 10^{18}$ GeV. However, at this time superstring models have not been developed to a degree where proton lifetime predictions can be extracted.

Magnetic monopoles can also induce proton decay in matter via the Rubakov-Callan effect.[29] The monopole catalysis cross section is independent of m_X, but quite sensitive to initial and final state interactions. For example, initial state interactions between a magnetic monopole and slow moving proton enhance the cross-section by $1/\beta$ (β = relative velocity). Therefore, in the case of hydrogen, one expects $\sigma(M + p \to M + e^+ + X) \simeq 3 \times 10^{-29}/\beta^2\ \mathrm{cm}^2$. Using that theoretical cross section, it has been shown[25] that water Cerenkov detectors are now providing monopole flux bounds near $10^{-15}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{sr}^{-1}$. At this workshop, initial and final state suppression or enhancement of monopole catalysis was discussed, but much theoretical work remains to be done.

A signal for $\Delta B = 2$ interactions would be neutron-antineutron oscillations.[30] That can occur via scalar exchanges in more complicated Higgs symmetry breaking scenarios. The predicted oscillation time is sensitive to the mass scale, m_S, of scalars responsible for the effect. In the case of free neutron oscillations, one crudely estimates the period to be $\tau_{n\bar{n}} \simeq 10^8(m_S/10\text{-}100\ \mathrm{TeV})^5$ sec. One can search for such oscillations with free neutrons or bound neutrons. In the latter case there are tremendous suppressions due to nuclear effects. Dover, Gal and Richard[32] have scrutinized those nuclear effects and find that the lifetime bounds on ^{16}O, $\tau_{n\bar{n}}$, can be translated into oscillation bounds

via $\tau_{n\bar{n}} \simeq 3 \times 10^{-12}\, T_{n\bar{n}}^{1/2}\, sec^{-1}$. Present bounds[33] $T_{n\bar{n}} \gtrsim 4.3 \times 10^{31}$ yr therefore, imply $\tau_{n\bar{n}} > 10^8$ sec. That provides a benchmark that free neutron oscillation experiments[26] must aim for if they are to be competitive. It should be noted that at the level of $\tau_{n\bar{n}} \simeq 10^8$ sec, one is probing exotic scalar effects at a mass scale of 10-100 TeV. From that point of view, such experiments are very complementary to SSC physics which is pretty much limited to scales $\lesssim$ 10 TeV.

Experimental Status

Two distinct types of detectors have been used to search for proton decay: water Cerenkov detectors which are very large and relatively inexpensive, and tracking calorimeters which have superior particle identification but cost more. Five such detectors are operating or completing upgrades. Although each of the detectors has recorded a number of candidate proton decay events, the rates are completely consistent with expected neutrino induced background events. Therefore, only bounds on partial proton lifetimes can be extracted from the data. Those bounds seem to indicate[24] that if the proton does decay, its lifetime is likely to be quite long $\gtrsim 10^{32}$ yr. To be capable of measuring that long a lifetime will require masses on the order of 1 kton or more. So, proton decay searches are only feasible with very large detectors.

Water Cerenkov detectors are particularly well suited for studying the $p \to e^+\pi^0$ decay expected to be mediated by super-heavy gauge bosons. The 3.3 kton IMB detector (which is the world's largest) and the 0.9 kton Kamiokande detector (which has superior energy resolution) currently give 90% C.L. bounds of 2.7×10^{32} yr and 1.1×10^{32} yr respectively for that important decay mode. The IMB limit translates into the bound[23] $m_X \gtrsim 7 \times 10^{14}$ GeV for the gauge boson mass and thereby rules out the so-called minimal SU(5) model. Those detectors also provide very good bounds on a wide variety of other decay modes that (depending on efficiency and number of background candidates) generally range from 10^{31} - 10^{32} yr. (See D.S. Ayres et al. in these proceedings.)[24] For example, the Kamiokande detector finds $\tau(p \to \bar{\nu}K^+) > 5 \times 10^{31}$ yr. That bound places a stringent constraint on scalar mediated and supersymmetric dimension 5 induced proton decay.

At present, the largest tracking calorimeter proton decay detector is at Frejus. Consisting of iron plates and flash tubes, it has a fiducial mass of 0.6 kton. Although still a relatively young detector, its outstanding tracking capabilities have allowed the Frejus group to already set the bound[24] $\tau(n \to \mu^+\pi^-) > 6 \times 10^{31}$ yr which is the best bound on that particular decay mode. During the next few years, longer running times as well as background studies should lead to about a factor of three improvement in the Frejus limits and thereby bring them to the 10^{32} yr level. Given its better particle identification for modes containing a charged lepton, this type of detector nicely complements the bigger water detectors.

Besides searching directly for proton decay, the large underground detectors have other very interesting capabilities. By not observing multiple proton decay candidate events, which would result from magnetic monopole catalysis, they have set flux limits near 10^{-15} $cm^{-2}sec^{-1}sr^{-1}$. In addition, they provide the best bound on n-$\bar{n}$ oscillations $\tau_{n\bar{n}} > 10^8$ sec. During the past few years, it has also become clear that large tracking calorimetry detectors provide a means of studying secondary leptons produced by particles from extraterrestrial sources such as Cygnus X-3.[4] Finally, the Kamiokande detector has been upgraded to look for solar neutrinos and thus help to solve the solar neutrino puzzle.[34]

Future

The large IMB, Kamiokande and Frejus detectors will continue to search for proton decay as well as other exotic phenomena (magnetic monopoles, n-$\bar{n}$ oscillations, ν oscillations etc.). Recent upgrades of IMB and Kamiokande detectors will allow partial lifetime limits to be pushed into the $10^{32} \sim 10^{33}$ yr range. They will be complemented by the Frejus detector which will also join the 10^{32} yr lifetime club.

The next big proton decay detector to come on line should be the Soudan II tracking calorimetry detector which is now under construction.[24] It will start off with a total mass of 1.1 kton which can be upgraded to 3.3 kton. That will be followed by a 2 kton liquid argon detector (ICARUS) in the Gran Sasso tunnel which is presently in an R&D phase.

For the more distant future, several very interesting proposals are starting to appear on the horizon. A 46 kton water Cerenkov super-Kamiokande detector and 20 kton liquid argon (or methane) ICARUS II detector were seriously discussed at this workshop. An ultimate 100-200 kton water detector was also studied. Such behemoth detectors appear capable of pushing limits on $\tau(p \to e^+\pi^0)$ to $\simeq 5 \times 10^{34}$ yr before being swamped by neutrino background.

Conclusions

Particle physics experiments using nonaccelerator techniques are likely to make substantial contributions to our understanding of fundamental physics in the 1990's. These experiments give the very real possibility of probing energy scales and phenomena which are not accessible to the SSC, with nucleon decay, monopole, and cosmic ray detectors, and a new generation of solar neutrino experiments. Should the observations of deep underground muons from cosmic sources be confirmed, the new particle physics which they imply can be further explored with new types of underground experiments. The sensitivities of experiments to search for magnetic monopoles and for high-energy astrophysical neutrinos will be increased by large factors in the next few years, giving the possibility to discover new phenomena.

The prospects are excellent that the new solar neutrino experiments now being constructed (both radiochemical and direct counting) will clarify or even resolve the solar neutrino puzzle, and will also test the proposal that matter effects in the sun can amplify neutrino oscillations. Should this mechanism be responsible for the lower than expected flux of solar neutrinos, the new experiments will determine previously unobservable properties of neutrinos. The sensitivity of experiments to detect double beta decay and neutrino masses will gradually improve over the next few years. The availability of large quantities of separated isotopes for research in the Soviet Union may revolutionize double beta decay searches within the next decade, as will the development of new

detectors based on quasiparticles in superconductors and phonons in crystals.

Recent progress in grand unified theories incorporating supersymmetry or superstring ideas holds out the possibility of testable predictions for the observation of proton decay. While many current models can give lifetimes in the observable range, none is likely to be ruled out by achievable experimental limits. Many models predict that nucleon decay final states will include kaons, and would have difficulty accommodating the observation of decays into pions. The sensitivity of nucleon decay experiments will increase gradually over the next few years as new detectors come into operation, existing detectors are upgraded, and new analysis techniques improve background rejection.

The first generation of large proton decay detectors have proved to be versatile instruments for studies in cosmic ray physics, magnetic monopole searches, and neutrino physics. The last topic includes neutrino oscillation experiments with atmospheric neutrinos and perhaps neutrino astronomy. A new generation of very large water Cerenkov and liquid argon TPC experiments could provide the ultimate sensitivity to proton decay, in addition to performing some very important neutrino physics experiments. The deployment of this next generation of sophisticated proton decay detectors, following on the heels of various experiments designed specifically for solar neutrinos, monopoles, and cosmic rays, seems certain to provide stringent limits on the existence of several kinds of new phenomena, and will contribute substantially to our knowledge of particle physics if any of these phenomena are actually discovered.

References

1. J.W. Elbert, Proceedings of the 2nd Conf. on the Intersections between Particle and Nuclear Physics, Lake Louise, Canada, 1986 (AIP Conference Proc. 150), edited by D. Geesaman, p. 1070; A.A. Watson, Proceedings of the 19th Int. Cosmic Ray Conf., La Jolla, USA, 9, 111 (1985).
2. A.M. Hillas, Nature 312, 50 (1984); Proceedings of the 19th Int. Cosmic Ray Conf., La Jolla, USA, 9, 407 (1985).
3. J. Grindlay, these proceedings.
4. M.L. Cherry, "Cygnus X-3: Is there Convincing Evidence for New Physics?", these proceedings.
5. M. Marshak et al., Phys. Rev. Lett. 54, 2079 (1985) and 55, 1965 (1985).
6. G. Battistoni et al., Phys. Lett. 155B, 465 (1985).
7. D. Ayres, Proceedings of the 2nd Conf. on the Intersections between Particle and Nuclear Physics, Lake Louise, Canada, 1986 (AIP Conference Proc. 150), edited by D. Geesaman, p. 1083.
8. F. Halzen, K. Hikasa, T. Stanev, submitted for publication (1986).
9. M.L. Cherry et al., "A Combined Cosmic Ray Muon Spectrometer and High Energy Air Shower Array", these proceedings.
10. B. Cabrera et al., "Magnetic Monopoles at the Parker Limit: New Prospects for Large Scale Detectors", these proceedings.
11. S.P. Ahlen and K. Kinoshita, Phys. Rev. D26, 2347 (1982); S.P. Ahlen and G.Tarle, Phys. Rev. D27, 688 (1983).
12. D.J. Ficenic et al., submitted to Phys. Rev. Lett. (1986).
13. T.K. Gaisser, G. Steigman, and S. Tilav, Phys. Rev. D34, 2206 (1986).
14. G. Auriemma, this meeting.
15. V. Stenger, "Extrasolar Neutrino Astronomy", these proceedings.
16. For an excellent review, see M. Doi et al., "Double Beta Decay and the Majorana Neutrino", Progress of Theoretical Physics Supplement No. 83, 1 (1985).
17. O. Fackler, this meeting, and Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, CA, July 1986.
18. D.O. Caldwell, "Double Beta Decay: Present and Future", these proceedings, and Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, CA, July 1986.
19. B. Kayser, "The Double Beta Decay - Neutrino Mass Connection", these proceedings.
20. B. Cabrera, D. Caldwell, and B. Saudoulet, "Low Temperature Detectors for Neutrino Experiments and Dark Matter Searches", these proceedings.
21. E.W. Beier et al., "Discriminating Among Scenarios to Resolve the Solar Neutrino Puzzle", these proceedings.
22. S.P. Mikheyev and A. Yu. Smirnov, Nuovo Cimento C9, 17 (1986), and L. Wolfenstein, Phys. Rev. D17, 2369 (1978).
23. W. Marciano, "Proton Decay Theory", these proceedings.
24. D. S. Ayres et al., "Nucleon Decay Experiments: Status and Prospects", these proceedings.
25. W. Marciano and D. Salvino, "Magnetic Monopole Catalysis of Proton Decay", these proceedings.
26. C. Y. Chang and R. N. Mohapatra, "On Neutron-Antineutron Oscillations", these proceedings.
27. S. Seidel and L. Sulak, this meeting.
28. H. Georgi and S. Glashow, Phys. Rev. Lett. 32, 438 (1974).
29. V. A. Rubakov, Nucl. Phys. B203, 311 (1982); C. G. Callan, Phys. Rev. D26, 2058 (1982).
30. V. A. Kuzmin, Pisma Zh. Eksp. Teor. Fiz. 13, 335 (1970).
31. M. K. Gaillard and D. Nanopoulos, "Ten Years Later", these proceedings.
32. C. Dover, A. Gal and J. M. Richard, Phys. Rev. D27, 1090 (1983).
33. M. Takita et al. (Kamiokande Collaboration), University of Tokyo preprint, 1986.
34. E.W. Beier, "The Status of the Search for Solar Neutrinos at KAMIOKANDE II", these proceedings.