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REVIEW OF FUTURE NUCLEON DECAY EXPERIMENTS

A.L. Grant
CERN, Geneva, Switzerland

ABSTRACT

At a time when the first results are becoming available from the IMB Water Cherenkov, the Kolar Gold Field and the Mont Blanc tracking calorimeters, it is appropriate to review the status and expected performance of the whole range of future nucleon decay experiments; from those under construction, Kamioka and Fréjus, to the future dreams of kilotons of liquid argon.

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1. INTRODUCTION

At the time when the first round of nucleon decay experiments is beginning to produce results on nucleon decay, it is appropriate to look critically at the status and expected performance of the whole range of second round experiments. The detectors discussed cover those just about to start taking data; Kamioka [1] and those under construction at Fréjus [2] and Soudan [3]. Proposals exist for conventional iron calorimeters for Gran Sasso [4,5] and the Kolar Gold Field, and for fully active liquid scintillator detectors at Homestake [6] and in the "Penn design" [7]. The far future belongs to the extrapolation of the tests done with a few kilos of argon, liquid [8,9] or gas [10], to multi-kilo ton detectors.

The common feature of all these new experiments is their initial large size, greater than 1000 t fiducial volume, and with the exception of the water Cherenkov detector, a modular construction which would allow a further increase in mass.

A second feature of the experiments is the high level of technical innovation in the proposals; from the massive 20" diameter photomultipliers used in the Kamioka experiment to the new concept of resistive plastics in the construction of drift tubes in the Soudan2 Proposal. It is already evident, for example, from the impact of the design of the limited streamer tubes [11] built for the NUSEX detector in the Mont Blanc tunnel on many of the calorimeters in the LEP experiments, that the design of proton decay experiments is at the forefront of detector technology.

The sheer size of these "multi-kiloton" experiments causes new problems, often underestimated, in the scale of production of the components and eventual installation underground. Fortunately, experience from the earlier experiments in the difficulties involved in working underground is now reflected in the modular construction of self-contained units which are built up into the final detector.

In the analysis of the experimental data from the calorimeter detectors, many old, and now rediscovered techniques are being developed, e.g. the use of multiple scattering to determine the direction of tracks. However, the competition of the very massive water Cherenkov detectors is still very strong. Also here the development of new ideas in analysis can give information on decays which at first sight would be undetectable. It is clear that to be competitive the calorimeter experiments must rely on very fine tracking to give a good picture of the possible decay candidates. In addition, they must have a redundancy to detect and differentiate from neutrino induced background the predicted supersymmetric decay modes such as $p \rightarrow K^+ \nu$.

2. STATUS OF THE EXPERIMENTS

A brief description is given of the various experiments, either under construction; proposals or future plans. Emphasis is placed on new technical developments in hardware or analysis in each, particularly with reference to their ability to detect the difficult decay modes predicted by supersymmetric grand unified theories. The ordering of the experiments is not random, it reflects the expectations of the groups as to the experimental time scale.

2.1 Kamioka Water Cherenkov

The Japanese water Cherenkov detector [1], situated in the Kamioka mine 300 km west of Tokyo, is now almost complete and ready to be filled with water for the first time.

The site of the experiment is an active lead and zinc mine with good rail access and a mountain rock cover of 2400 to 2700 m.w.e. It is not as deep as the European experiments in their alpine road tunnels, but somewhat better than most North American sites. A schematic drawing of the specially constructed

cavity and access tunnels is shown in fig. 1. The steel water tank of 3420 m^3 and the 1050 20" diameter photo tubes are installed ready for use.

These very large photo tubes, the result of a fruitful collaboration of the Japanese groups and the Hamamatsu Corp., qualitatively change the prospects of the detector by allowing the reliable detection of the weak signals from charged hadrons in proton decay. The system will be triggered on the total energy of the event summed over all pulses. There is no attempt to provide individual timing for each photomultiplier, however, the time structure of the total signal is digitized in bins of 100 ns for 5 μs to enable the detection of the delayed electron from one or more muon decays.

The expected signals from the two-body decays of the nucleon are shown in fig. 2, one hemisphere plotted against the other. This level of photon statistics would allow clean separation of different decay modes. Table 1 gives the expected performance for all SUSY decay modes [12]. As always it is difficult to separate the single track and the ν decay modes from ν induced background.

2.2 The Fréjus Experiment

The Fréjus experiment, a collaboration of European laboratories at Orsay, Palaiseau, Saclay and Wuppertal is situated in the Modane Underground laboratory in a new road tunnel east of Grenoble in France. There is a reasonable sized cavity, 4000 m^3 , at a depth of 4500 m.w.e.

The design of the Fréjus detector is now fixed, full scale production of the $6 \times 1.5 \text{ m}^2$ flash chamber modules has started and is expected to reach a production rate of 5 modules per day. It is expected to have 400-500 t installed by the end of the year and 1500 t fully operating by the end of 1984. The cavity is now ready and installation of power, gas supplies, computer, etc. under way.

TABLE 1

Performance of Kamioka Water Cherenkov for SUSY decay modes

Decay	# pe	ΔE_{total}	ΔE_{μ}	Comment
1) $P \rightarrow \mu^+ K_S^0$ $\quad \quad \quad \rightarrow \pi^0 \pi^0$	2000	3.6%	μ 13% 4 γ 's	Easily identified
2) $P \rightarrow \mu^+ K_S^0$ $\quad \quad \quad \rightarrow \pi^+ \pi^-$	540	90% of dks 17.3%	μ 13% 2 π 's	16% 3 rings K_S^0 mass 75% 2 rings - difficult
3) $P \rightarrow K^+ \nu$ $\quad \quad \quad \rightarrow \mu^+ \nu$	130		μ 9%	Background $\bar{\nu} N \rightarrow \mu^+$ in same μ energy bin 2-3/year
4) $P \rightarrow K^+ \nu$ $\quad \quad \quad \rightarrow \pi^+ \pi^0$	700		E_{K^+} 12%	Rarely 3 rings much ν inelastic background
5) $n \rightarrow K_S^0 \nu$ $\quad \quad \quad \rightarrow \pi^0 \pi^0$	1600		E_{K^0} 7%	Very rare to reconstruct K_S^0 , ν background
6) $n \rightarrow \nu K_S^0$ $\quad \quad \quad \rightarrow \pi^+ \pi^-$	230		E_{K^0} 8%	50% of K_S^0 reconstruct not much ν background

Fig. 3 shows a schematic drawing of a single super module of 8 detector planes and 2 trigger planes. It is hoped to have the first of these $6 \times 6 \text{ m}^2$ units installed and working in the cavity by the end of May 1983.

The detector well satisfies the need of fine sampling, 3 mm iron, and fine lateral cell size, 5 mm, to provide good separation between electrons and hadrons on the basis of visible electromagnetic showers. The flash chamber planes are triggered by planes of Geiger tubes $1.4 \times 1.4 \text{ cm}^2$ cross section, between each super module of flash chamber, e.g. 1.4 radiation lengths of material. The intrinsic resolution of these tubes is $\sim 200 \text{ ns}$,

adequate for a simple coincidence trigger, but insufficient to give decay at rest delay times for K's or π 's or track direction by time-of-flight.

The direction of muons from, for example, kaon decay can be measured by the increase in multiple scattering, 60% useful, and the positron from μ^+ decay can be seen by using a long HT pulse on the flash chambers, 10 μ s. The last feature has been tested in the laboratory and works at the expense of an increased gas flow. To save cost, the time of the delayed signal is digitised by TDC's connected to groups of 8 channels, 4 cm in space, instead of the single channel of the normal readout electronics.

2.3 Soudan2 Experiment

The Soudan2 detector [3] proposed by the Minnesota, Argonne, Oxford, RAL and Tufts Collaboration to be installed in a mine in the Tower-Soudan Historical State Park, bears many similarities to the Fréjus experiment. Both detectors are fine grained tracking calorimeters, modular in construction, with iron plates sandwiched between gaseous tracking chambers. Both detectors are of similar size, Soudan2 will start at 1000 t with an option to extend to 5000 t. Though the Soudan2 will start a year after Fréjus it is clear that there will be strong competition between them.

The option taken by the Soudan2 Proposal has been to trade the good two track resolution, but digital readout of the flash chambers, for the advantage of analog pulse height measurement of dE/dx in drift chambers. The single track spatial resolution of the two detectors is comparable, although Soudan2 has an advantage in space points rather than the uncorrelated stereo views of the flash chambers.

The potential of the dE/dx measurement in identifying tracks and telling their direction of motion is shown in fig. 4. Also the intrinsic timing will allow the detection of the delayed e^+ from μ^+ decays at rest.

The Soudan2 Proposal is now authorised both by DOE and SERC, and the detailed design of the drift chamber scheme is underway. Two 1-2 t prototypes are being built on rather different lines, both technically inovative and worth describing in some detail.

The proposal of the Argonne Group is to build planar drift units of $5 \times 0.5 \text{ m}^2$. The ionized electrons drift over 50 cm down a 1 cm wide gap to an anode wire 5 m long running down one edge of the chamber. A space point is obtained from drift time, an anode and a cathode strip linking several chamber units. The difficult step in the construction is to provide, at reasonable cost, the drift field shaping electrodes. These are made from a mylar sheet with a minimum number of printed copper electrodes connected by a resistor chain to a 10 K high tension source. Irregularities in the field are smoothed by coating the mylar with resistive ink. Chambers have been laboratory tested and a 2 t fully equipped prototype is under construction. The size of the project is best gauged by the fact that 10 000 such chambers have to be built.

A novel alternative for a construction scheme has been proposed by the Oxford Group. Schematic drawings of the detector are shown in figs 5 and 6. In this design the ionized electrons drift down hexagonal resistive plastic tubes held between shaped 2 mm thick iron plates. The advantage of this layout is the small number of electrical connections and hence ease of construction. The HT and insulation from the iron is supplied by a single sheet of mylar, with copper electrodes on the tube side, "woven" between the steel plates.

The problem with the design is to obtain a plastic of the correct resistivity, 10^{10} - $10^{12} \Omega$ per $\square$, and adequate uniformity. Too little resistance and the tubes never reach the delicate dynamical equilibrium between leakage and enough charge induced on the tube surface to give the right field shape; too much resistance and the field quickly becomes unstable.

A one ton prototype detector is under construction and will be compared with the one from Argonne before freezing the design at the end of this year. The proposal calls for the first 50 t detector to be installed in the mine by mid 1984 and the complete detector to be operating by the end of 1985.

2.4 Kolar Gold Field Experiment

As a result of their experience with the small detector in the Kolar Gold mine, the groups involved have proposed an extension of the experiment with a new detector with a mass of up to 1000 t.

A new cavern of 3000 m³ would be constructed at a depth of 2100 m, large enough to contain three 6 x 6 x 6 m³ modules. The detector would be based on the same principle as before, i.e. thick walled iron proportional tubes giving position and dE/dx measurements. In the new detector the tubes would be smaller in cross section, 5 x 5 cm² giving better spatial resolution.

The proposal is still at the design stage, but in principle a one kilo-ton detector could be ready by the "end of 1984".

2.5 The Gran Sasso Project

The construction of the Gran Sasso underground laboratory [4] has started. The project calls for three large caverns, each the order of 11 x 16 x 100 m³, complete with good access and user facilities. Fig. 6 shows the layout and cross section of the tunnels. To date, the central cavern and a single access road has been excavated, but still has to be finished. Completion of the concrete lining, installation of power, ventilation etc. awaits further funding

Two projects exist for detectors to be installed in the finished cavern. GS1, an extension of the NUSEX experiment in the Mont Blanc tunnel, and the GUD flash chamber detector proposed at the Rome Workshop in 1981 [5].

GS1 is a fine grained tracking calorimeter based on the same structure and limited streamer tubes used as in the NUSEX experiment. Experience has shown that a lower density and finer sampling are desirable, hence iron plates of 5 mm, instead of 10 mm, will be used. A 1000 t detector is foreseen with means of extension to 3000 t. Minor improvement of the readout electronics will increase the detection efficiency of the delayed e^+ from μ decay at rest. The finer sampling will also improve the measurement of multiple scattering to give the direction of flight of the tracks (fig. 8).

The time scale for the proposal would allow the experiment to be taking data with a full 1000 t detector by the end of 1985.

Little has changed in the proposal for the very massive GUD flash chamber detector since the presentation in October 1981. Construction of the large area, $3 \times 1 \text{ m}^2$, resistive plate chambers [13] for a current $n\bar{n}$ oscillation experiment by the same group is under way. These chambers allow the very fast trigger and time-of-flight measurements crucial to the success of this very large 10 000 t detector.

2.6 Liquid Scintillator Detectors

Two proposals exist and are being strongly upheld by their authors as the best possible solution for a next generation nucleon decay detector. The advantages of a fully active calorimeter are great. The energy resolution $\sim 4\%$, is at the level of the energy smearing due to Fermi motion and the potential time resolution is excellent $\leq 2\text{ns}$. This timing would in principle allow the detection of the delayed coincidence from a K meson decay at rest, an unambiguous signal for one of the predicted SUSY decay modes. Disadvantages are however significant; inherently poor spatial resolution, poor containment of nucleon decays and cost, especially in electronics if the timing ability is to be

used to its full potential. The lack of two track spatial resolution is a serious effect, it implies that spurious energy measurements would often occur due to the undetected interactions of hadrons.

The Homestake proposal is for a 1400 t stack of 2000 liquid scintillator modules each $.3 \times .3 \times 8 \text{ m}^3$. At present 200 of these elements are being manufactured to construct a veto plane to surround the existing ^{37}Cl solar neutrino tank. This detector, though of a poor aspect ratio, for a nucleon decay detector, will provide an excellent test of working with liquid scintillator deep underground.

The second proposal is the result of a design study by the University of Pennsylvania based on the extrapolation in size of an existing accelerator neutrino detector at BNL. A 2600 t detector is proposed with a fiducial volume of 1300 t. The problem of spatial resolution is overcome by putting xy planes of proportional drift tubes between each liquid scintillator unit. It is clear that the detector proposed is by far the most highly instrumented, with a corresponding high performance and cost.

2.7 Liquid Argon Detectors

There are several ideas for liquid [8] or high pressure gas [10] Argon detectors working in a TPC-like mode. There is even a proposal for a 3000 t liquid argon bubble chamber [9] with a 50% duty cycle to study proton decay. Liquid argon has many beautiful properties as a detector medium: energy measurement by scintillation light in the UV, particle identification from Cherenkov light and fast timing. TPC quality tracks can be obtained after drifting over reasonable distances in the liquid. High pressure gas detectors, 500 atm., have the same properties and the benefit of gas amplification of the signals at the anode wires. At present several small scale tests are under way. However, the main problems of cost and deployment underground still remains to be overcome.

3. CONCLUSIONS

Table 2 shows a summary of the main points of the active and proposed experiments. It is a substantial list corresponding to a massive expenditure of manpower and money. By the end of 1985 there will be at least two large water Cherenkovs and two large fine grained tracking calorimeters in operation. In a rational world this would seem to be an adequate investment, at least until the proton lifetime has been measured!

TABLE 2
Summary of future experiment

Detector	Site	Type	Size k tons	Starting date	Comments
Kamioka	Kamioka mine Japan	water Cherenkov	1.0	early 1983	good p.e. statistics
Fréjus	Modane underground laboratory	flash chamber	1.5	end 1984	track dir. by m.s.
Soudan2	Soudan -Tower mine	drift chamber	1.→5.	end 1985	track dir. by dE/dx
Kolar gold	Kolar mine India	prop tube	1.0	end 1984?	dE/dx
GUD	Gran Sasso	flash chamber	10.0	proposal	fast timing ≤ 2ns
GS1	Gran Sasso	limited streamer tubes	1.→3.	proposal	track dir. by m.s.
"Penn design"	?	liquid scintillator prop. tubes	2.6	proposal	dE/dx and good tracking
Homestake	Homestake mine	liquid scintillator	1.4	proposal	dE/dx and good timing

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FIGURE CAPTIONS

- Fig. 1 Layout of the Kamioka proton decay experiment.
- Fig. 2 Monte Carlo simulation of some nucleon decay modes in the Kamioka detector.
- Fig. 3 Detail of the structure of a super module for the Fréjus detector.
- Fig. 4 Possibility of determining the direction of a stopping track using dE/dx measurement. The total ionization of the last third of the track, I_2 , is plotted against that of the first third, I_1 .
- Fig. 5 Schematic drawing of the structure of the resistive tube calorimeter.
- Fig. 6 Construction of resistive tube calorimeter, showing the layout of the anode wires and cathode strips.
- Fig. 7 (a) General plan of laboratory (three "Main Tunnels" connected by a linking tunnel) and access to it;

 (b) Cross-sectional view of Main Tunnels.
- Fig. 8 Efficiencies for various incidence angles for an apparatus having 0.5 cm of iron, 2.2 cm between the tube planes. The efficiency is the fraction of tracks found in the correct direction:

 (a) refers to σ_x equivalent = 3 mm and $\sigma_y = 3$ mm;
 (b) refers to $\sigma_x = 3$ mm and $\sigma_y = 3$ mm.

Fig. 1

Fig. 2

MODULAR STRUCTURE OF THE DETECTOR

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8