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THE HOMESTAKE TRACKING SPECTROMETER*

A ONE-MILE-DEEP 1400-TON LIQUID-SCINTILLATION NUCLEON-DECAY DETECTOR

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ABSTRACT

We describe a proposed nucleon decay detector able to demonstrate the existence of nucleon decay for lifetimes up to 5×10^{32} yr. The proposed instrument is a self-vetoed completely-active 1400-ton liquid scintillation Tracking Spectrometer to be located in the Homestake Mine at a depth of 4200 mwe, where the cosmic ray muon flux is only $1100/\text{m}^2/\text{yr}$, more than 10^7 times lower than the flux at the earth's surface. Based on computer simulations and laboratory measurements, the Tracking Spectrometer will have a spatial resolution of ± 15 cm (0.32 radiation lengths); energy resolution of $\pm 4.2\%$; and time resolution of ± 1.3 ns. Because liquid scintillator responds to total ionization energy, all neutrinoless nucleon decay modes will produce a sharp ($\pm 4.2\%$) total energy peak at approximately 938 MeV, thereby allowing clear separation of nucleon decay events from atmospheric neutrino and other backgrounds. The instrument will be about equally sensitive to most nucleon decay modes. It will be able to identify most of the likely decay modes (including $n \rightarrow \nu + K_s^0$ as suggested by supersymmetric grand unified theories¹), as well as determine the charge of lepton secondaries and the polarization of secondary muons.

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I. GENERAL EXPERIMENTAL ASPECTS OF THE NUCLEON DECAY SEARCH

A. THE SIGNAL

From a model independent point of view, the only reliably known features of the nucleon decay process are (for free protons) a total energy release of 938 MeV and a vanishing vector sum of final state particle momenta. Similar relations exist for bound nucleons, but are somewhat smeared out by the Fermi momentum of the decaying nucleon.

Many theoretical models and calculations for nucleon decay have been proposed.² These models provide a wide range of possible nucleon decay final states. For example, on the lepton side, electrons, muons, and neutrinos are expected with varying probabilities, while the decay-product hadrons range from pions and kaons to the vector mesons rho, eta and omega. Further degrees of freedom are proposed in various calculations: predominance of three body decay modes³, the Goldhaber effect⁴ (decay of a bound nucleon to a ~700-MeV electron together with an excited nucleus), three-lepton final states⁵, etc.

In this situation, it is evident that the critical requirements for a successful experiment are that it be sensitive to as wide a range of final states as possible and that the model independent features of 938 MeV energy release and final state momentum balance be utilized to the maximum extent possible.

B. THE BACKGROUND

The known backgrounds in nucleon decay experiments are produced by cosmic ray muons (either directly or as a result of cascades produced through their electromagnetic or nuclear interactions) and by cosmic ray neutrinos. Various unknown backgrounds, such as "Kolar events", monopoles, the decay of cosmological relic particles, liberated quarks, etc. are also possible.

The most reliable technique for the suppression of the muon-produced backgrounds is to perform the experiment at as great a depth as possible so as to utilize the rock overburden as a massive muon absorber. Because the remnant cosmic ray muon flux is a rapidly

decreasing function of depth, factors of two or three in depth typically yield two or more orders of magnitude reduction in the muon flux and hence in all muon-associated backgrounds.

The neutrino backgrounds are independent of depth and must be dealt with by detector design alone. In view of the wide variety of possible nucleon decay final states, the best strategy is to maximize the information-gathering ability of the detector, i.e. energy resolution, spatial resolution, time resolution, etc.

C. EXPERIMENTAL GOALS AND METHODS

The prime goal of any nucleon decay experiment at this time must be the clear demonstration of the existence of the nucleon decay process. Once the existence of nucleon decay has been firmly established, it will then be desirable to determine branching ratios, the nucleon total lifetime, the number, charge state and polarization of the final state leptons, the nature of the hadronic state, etc.

The design of a nucleon decay experiment involves the optimization of many conflicting requirements. The fundamental requirement of very large mass imposes financial and physical constraints which limit the choice of detector. In addition, mine/tunnel safety considerations reduce the desirability of many materials, such as cryogenic liquids and low flash point solvents. Further compromises result from the desire to contain nucleon decay events in a finite sized detector (best with high Z materials) as well as to minimize the effects of nuclear binding and to provide a significant sample of free nucleon decays (best with low Z materials).

In view of the complex nature of the nucleon decay problem, we believe that a variety of experiments, each optimized in particular ways, will provide the most reliable information on nucleon decay for lifetimes up to 10^{33} years. If it is necessary to search for nucleon decay beyond this range, it will probably be appropriate to concentrate world-wide resources on one or two enormous, highly sophisticated experiments. However, the results and experience obtained through performing a reasonable variety of relatively small experiments will be essential for the proper design of the ultimate nucleon decay experiment.

II. DESCRIPTION OF THE HOMESTAKE TRACKING SPECTROMETER

A. GENERAL PROPERTIES OF LIQUID SCINTILLATOR

The fundamental property of liquid scintillator that makes it desirable as a nucleon decay detection medium is its ability to convert the kinetic energy of charged particles to visible photons. The scintillation response is linearly related to the energy deposit for all but heavily ionizing particles. Even for such particles, the empirically well-established Birks' law⁶ can be used to linearize the scintillator output.

Since the energy deposit needed to produce each optical photon is about 200 eV, a nucleon decay event in liquid scintillator would yield about 5×10^6 photons. With an easily achievable 2% photon collection efficiency and 10% conversion efficiency to photoelectrons, about 10^4 photoelectrons would be detectable, resulting in a theoretical energy resolution of $\pm 1\%$.

Since liquid scintillator responds linearly to energy deposited, a nucleon decay detector utilizing this material will be useful for all possible final state particles (other than neutrinos), thereby permitting a relatively decay-mode independent experiment. The fundamental model independent nucleon decay signature in such a detector would be the release of optical photons equivalent to 938 MeV.

In addition to its ability to determine total energy, liquid scintillator has the property of producing useful optical photons on an extremely rapid time scale. Excellent time resolution (typically ± 1 ns) is therefore obtained. With this quality of time information, the time-of-flight technique will allow determination of the sense of motion of final state particles and therefore verification of the second model independent nucleon decay feature--vanishing of the sum of the final state momenta.

B. DESIGN FEATURES OF THE HOMESTAKE TRACKING SPECTROMETER

The Homestake Tracking Spectrometer (see Fig. 1) consists of 1406 tons of liquid scintillator contained in 1872 modules each 8 m long, with a 30 cm x 30 cm cross section, and viewed by two 5-inch

hemispherical photomultiplier tubes. The PVC counter modules, each of which is lined with an aluminized polyester reflector to provide good light collection, are arranged in stacks of crossed X-Y arrays to provide detailed tracking information for the nucleon decay secondaries. The detector will be housed in a new room on the 4850-foot level of the Homestake mine, adjacent to the existing Penn-Brookhaven water Cerenkov detector-solar neutrino room.

The design parameters of this instrument are summarized in Table I.

III. EXPECTED PERFORMANCE OF THE HOMESTAKE TRACKING SPECTROMETER

The performance of this detector has been carefully evaluated using computer simulation techniques and laboratory tests on a 9-ton prototype stack and on full 8-meter prototype detector elements.

A. ENERGY RESOLUTION

An efficient liquid scintillator having extraordinarily high stability, transparency, and flash point, together with low cost and toxicity has been specially developed for use in the Tracking Spectrometer. Our mineral oil-based scintillator has a light output equal to that of the best commercially available scintillators but provides a superior attenuation length of 7 meters and a transparency lifetime estimated at 30 years.

A typical pulse height spectrum for cosmic ray muons passing through an 8-meter module is shown in Fig. 2. The observed peak corresponds to 54 MeV of ionization energy loss and has a width of $\pm 6.8\%$. Since nucleon decay will release 938 MeV, we expect a 17-fold increase in the total number of detected photoelectrons, or a factor of $\sqrt{17}$ improvement in the overall energy resolution, i.e. a final value of 1.6%. With nonlinearity of the scintillation process, Fermi momentum smearing, and incomplete containment of final state particles properly taken into account in our computer simulations, we expect an energy resolution of $\pm 4.2\%$ to be realistically possible for nucleon decay.

Fig. 3 presents the observed pulse height spectrum for a light-emitting diode. The $\pm 4.9\%$ width of the peak provides the basis for our estimate of 8800 collected photoelectrons per 938 MeV of energy deposited in the scintillator.

B. TIME AND POSITION RESOLUTION

In Fig. 4 we present results from measurements of cosmic ray muons in a 46-module, 9-ton prototype stack located in a surface laboratory at the University of Pennsylvania. The modules for this stack are 12-foot-long, 1-foot-diameter liquid-scintillator-filled PVC counters, otherwise identical to the proposed Tracking Spectrometer modules. We have triggered one of the twelve-foot modules using pairs of crossed elements located respectively at 45 cm, 180 cm, and 315 cm from one end. For each trigger, we have plotted the pulse height difference vs the time difference for the two phototubes at the ends of the 12-foot module. The X- and Y-projections of the scatter plot are also shown in the figure. From the observed widths of the pulse height and time peaks, we determine the position resolution to be ± 12 cm and ± 15 cm, respectively. We therefore have two independent methods for localizing the energy deposited and hence the particle trajectory in each module. Certain events, such as those in which a single module has two independent hits (which may be ambiguous using phototube information from that module alone) will still be interpretable by introducing position information produced by the crossed modules in adjacent layers.

If we use the average time of firing of the two phototubes in each module, we can establish the time of flight of each particle such that localization of the nucleon decay vertex will be possible to an accuracy of ± 15 cm. Unambiguous determination of the sign of the momentum will likewise be possible for particle trajectories penetrating at least two modules.

C. EVENT SIMULATION USING THE MONTE CARLO METHOD

Computer simulations of the detector response to various nucleon decay final states have been performed. The Monte Carlo program includes a full simulation of the propagation of electro-

magnetic showers⁷, muons, pions, and kaons.

In Fig. 5 we show a typical Monte Carlo simulation of a $p \rightarrow e^+ \pi^0$ nucleon decay event as seen in the Tracking Spectrometer. The total visible energy for this event was 913 MeV. In the "energy" view, the location of each number indicates the position of a triggered module, while the number itself indicates the observed energy deposited in that module in units of 10 MeV. The nucleon decay event took place above the point labelled "ND", while the vector from "ND" to "PZ" marks the initial direction of the π^0 . Similarly, the vector from "ND" to "E+" indicates the initial direction of the positron. In the "time" view, the time of firing of each module (in ns) is indicated. From the information in this view, the presence of a decay rather than an interaction vertex at the point "ND" is obvious.

The results of 400 simulations for two typical nucleon decay modes are presented in Figs. 6 and 7. Events in which more than 50 MeV appears in the outermost 30 cm of the detector (the "anti" layer) have been excluded. For neutrino emitting modes, neutrino-escape peaks are observed at energies less than 938 MeV. Decay channels with charged lepton secondaries, such as $p \rightarrow e^+ \omega$ (Fig. 6) and $n \rightarrow e^+ \pi^-$ (Fig. 7), exhibit relatively sharp peaks at 938 MeV, as expected.

The results of the Monte Carlo calculations of the detection efficiencies for various nucleon decay modes are presented in Table II. The table lists average event lengths and detection efficiencies for 80% and for 90% energy containment. To obtain the desired energy resolution of $\pm 4.2\%$, our Monte Carlo calculations indicate that 90% containment is sufficient. The detection efficiencies vary from 35% to 77%, with a mean of 60%. Within a factor of two, therefore, the Tracking Spectrometer constitutes a decay-mode-independent nucleon decay detector. The total fiducial mass is approximately 1400 tons $\times$ 60% or 840 tons. We note, parenthetically, that an ideal cubic detector of the same mass would have an efficiency of about 65%.

D. EVALUATION OF BACKGROUNDS

At the 4200 mwe depth of the Homestake laboratory, the

integrated flux of cosmic ray muons over the full spectrometer area is 400,000 muons per year. With an expected 99% rejection of entering muons by the top anticoincidence layer, about 4000 unvetoed muons per year will remain. The tracking (rejection factor >50), timing (>50), and energy resolution (>20) capability of our detector will permit us to recognize and reject these remaining throughgoing muons. Similar arguments convince us that stopping or interacting muons will also be easily rejected. The raw trigger rate for muons of about 1 per minute will allow us to record all muon information on magnetic tape for detailed offline analysis.

The remaining known source of background is cosmic ray neutrino interactions. Neutrinos interacting inside the detector can be shown to be more important than those interacting in the rock surrounding the detector. Because of the excellent energy resolution of our detector, only those neutrino interactions depositing 938 ± 50 MeV in the detector are potential background problems for nucleon decay. Except for neutral current interactions, the detector will measure the total neutrino energy in the signal generated by the interaction secondaries. The flux of muon neutrinos at 938 MeV is $3.7 \times 10^{-3} / \text{cm}^2 / \text{sec} / \text{sr} / 100 \text{ MeV}$, while the electron neutrino flux in the same window is $1.7 \times 10^{-3} / \text{cm}^2 / \text{sec} / \text{sr} / 100 \text{ MeV}$. Using the sum of these fluxes integrated over solid angle and the known neutrino interaction cross section of $0.5 \times 10^{-38} \text{ cm}^2$ leads us to expect a total of 8 neutrino interactions per year under the nucleon mass peak.

We expect that a further factor of 10 suppression of this neutrino background can be made using simple event reconstruction techniques such as momentum-balance determination. The anticipated neutrino background is therefore less than .8 per year. Since atmospheric neutrinos are the dominant source of background in our detector (probably true only for detectors located deeper than 3500 mwe), the background limit of our experiment will be

$$\frac{6 \times 10^{29} \text{ nucleons/ton} \times 1400 \text{ tons}}{.8 \text{ background events/yr}} = 10^{33} \text{ yr.}$$

IV. SUMMARY

The unique features of our Tracking Spectrometer approach to the search for nucleon decay are the extremely good energy and time resolution and reasonable position resolution together with the low muon background environment provided by our mile-deep location.

The value of the $\pm 4.2\%$ energy resolution is particularly evident in allowing reduction of the internal cosmic ray neutrino background from a raw rate of 280 events/year in the 0.2-5 GeV region⁸ to only 8 per year under the 938 MeV nucleon mass peak. Without good energy resolution, we believe the same factor of 35 reduction could be obtained only through bubble-chamber-quality spatial information.

The ability to distinguish decay from interaction vertices provided by our ± 1.3 ns time resolution is an additional strong guarantee that true nucleon decay events will be distinguishable from background.

Assuming that one event per year is the lowest event rate at which nucleon decay can be observed, the Tracking Spectrometer will have a sensitivity corresponding to a nucleon total lifetime of

$$\frac{6 \times 10^{29} \times 1400 \text{ tons} \times .6 \text{ (mean detection efficiency)}}{1 \text{ event/yr}}$$

$$= 5 \times 10^{32} \text{ yr.}$$

V. EXPERIMENTAL STATUS AND PLANS

We will be installing a 75-ton, 100-module detector section in our existing laboratory in the Homestake mine during the summer of 1982. Completion of the 1400-ton, 3-stack detector is presently awaiting approval of full funding. With expeditious approval, the complete detector would be operational by the spring of 1984. If the initial physics results with this and other nucleon decay experiments indicate that a larger detector is desirable, the great stability of the rock at Homestake would allow construction of

detectors with cross sections as large as 16 m x 16 m and virtually unlimited lengths.

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PARAMETERS OF THE HOMESTAKE TRACKING SPECTROMETER

DEPTH:	4200 meters u.e.
RESIDUAL COSMIC RAY MUON FLUX:	1100/m ² /year
OVERALL SIZE:	8 m x 8 m x 20 m
TOTAL MASS:	1426 tons
PHOTOELECTRONS per 930 MeV:	9820
ENERGY RESOLUTION:	+/- 4.2%
TIME RESOLUTION:	+/- 1.3 ns
SPATIAL RESOLUTION:	+/- 15 cm or 0.32 rad. lengths
DECAY MODE SENSITIVITY:	- ALL
LIFETIME SENSITIVITY:	5 x 10 ⁻³² years
COST:	\$4.2M

Table I. Design parameters of the Homestake Tracking Spectrometer.

EVENT LENGTH (L) AND DETECTION EFFICIENCY (e)
FOR 1500 M² DETECTOR

DECAY MODE	PERCENTAGE OF ENERGY CONTAINED			
	80%		90%	
	L(m)	e(%)	L(m)	e(%)
P → E+ P1 0	4.3	48	5.8	35
P → E+ RHO 0	1.2	82	1.5	77
P → NU P1 +	0.9	88	1.5	77
N → E+ P1 -	3.0	59	4.0	51
N → E+ RHO -	1.8	74	3.0	59
N → NU P1 0	2.4	65	3.0	59

e (mean) (8m X 8m X 24m) 59% 60%
e (mean) (11.4m)² 73% 65%

Table II. Results of Monte Carlo calculation of detection efficiency for various nucleon decay modes. Requiring 90% energy containment, a mean detection efficiency of 60% for our 8 m x 8 m x 24 m detector is obtained.

NEW HOMESTAKE EXPERIMENTAL AREA

Figure 1. The proposed 5000 m³ Homestake experimental room showing the Tracking Spectrometer and the Solar Neutrino area. It is planned to build the new room adjacent to the existing 2000 m³ room at a depth of 4200 mwe.

Figure 2. Typical pulse height spectrum for cosmic ray muons passing through an 8-meter test module. The muon energy loss is 54 MeV, while the observed energy resolution is $\pm 6.8\%$.

Figure 3. Pulse height spectrum for a light-emitting diode located 2.7 m from one end of an 8-meter test module. The amplitude of the light pulses corresponds to 54 MeV. From the observed standard deviation of 4.9%, we calculate that the signal corresponds to 415 photoelectrons. This result implies that, for 938 MeV (the energy deposit expected for most nucleon decay events), we will observe a total of 8800 photoelectrons.

Figure 4. Position resolution results obtained from measurements of cosmic ray muons in a 46-module, 9-ton prototype stack. For muons passing at three different locations through a test module, the scatter plot shows the pulse height differences vs the time differences for the two phototubes at the ends of the module. From the observed widths of the projected pulse height and time peaks, the position resolution is determined to be ± 12 cm and ± 15 cm, respectively. Two independent methods for localizing the energy deposited and hence the particle trajectory in each module are therefore available.

STIMULATION NUMBER 2
NUCLEON DECAY COORDINATES: 112, 1143, 411, CM
EYOT = 115.9 EVIN = 112.6 SANTZ = 8.8 NMOD = 23

Figure 5. Monte Carlo simulation of a typical $p \rightarrow e^+ \pi^-$ nucleon decay event as seen in the Tracking Spectrometer. In the "energy" view, the location of each number indicates the position of a triggered module, while the number itself indicates the observed energy deposit in that module in units of 10 MeV. The nucleon decay event took place above the point labelled "ND", while the vector from "ND" to "E+" marks the initial direction of the π^- . Similarly, the vector from "ND" to "E+" indicates the initial direction of the positron. In the "time" view, the time of firing of each module (in ns) is indicated. From this information, the presence of a decay rather than an interaction vertex at the point "ND" is obvious.

Figure 6. Monte Carlo calculation of pulse height spectrum produced by the decay mode $p \rightarrow e^+ \omega$. Only events in which less than 50 MeV was deposited in the outermost 30 cm of the detector (the "anti" layer) have been plotted. The calculation includes the effects of imperfect energy containment, Fermi momentum smearing, and liquid scintillator nonlinearity and finite resolution. When a muon decay (produced following decay of a π^+) was detected, (detection efficiency = 98%), we corrected for loss of rest mass from the prompt energy release by adding 106 MeV to the observed pulse height.

Figure 7. Monte Carlo calculation of pulse height spectrum produced by the decay mode $n \rightarrow e^+ \pi^-$. The remarks for Fig. 6 apply except that, because the π^- undergoes nuclear capture in liquid scintillator, the full 938 MeV energy release is visible in the prompt pulse.