REVIEW OF PROTON LIFETIME EXPERIMENTS*

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1. Introduction

The goal of this talk is to review experiments, planned or in progress, to study the instability of the nucleon with special emphasis on those experiments which have yielded some preliminary results. I will not discuss predictions or experiments associated primarily with $\Delta B = 2$ transitions which would include the neutron oscillation experiments being conducted at reactors or at accelerators yielding large neutron flúxes. Much of what I will say has recently been presented at the Second Workshop on Grand Unification which took place at Ann Arbor, Michigan, from the 24–26 of April, 1981.

2. Predictions of nucleon lifetimes and branching modes

Theories of Grand Unification (GUTS) predict massive gauge bosons X which couple to a pair of quarks and to leptons and antiquarks as indicated in figure 1a. A consequence of this coupling along with the requirement of, for example, SU_5 that $\Delta B = \Delta L$ is that the nucleon can decay as shown in figure 1b. If the mass of the gauge boson, M_X, is much greater than other masses involved in the decay, the amplitude for the decay will contain a propagator $1/M_X^2$ and the lifetime of the nucleon will be proportional to M_X^4 or

$$\tau_N = CM_X^4. \tag{1}$$

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To estimate τ_N, the twofold task consists of first evaluating M_X and then C. The problem of extrapolating the coupling constants α_S, α_W and α_U to the grand unification mass is discussed by numerous authors [1] and in particular, the extrapolation of α_S depends

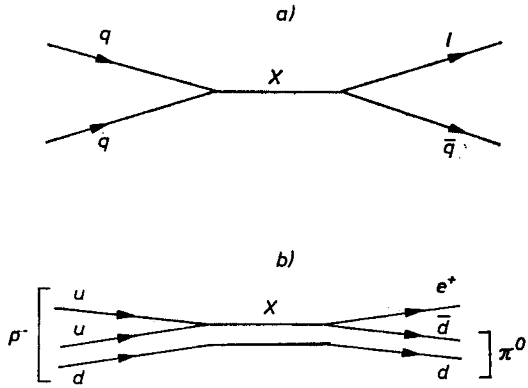

Fig. 1. a) Coupling of a massive boson X to a pair of quarks and to a lepton and antiquark b) Proton decay by means of a massive gauge boson X. Numerous processes in addition to the above can be sketched for various decay modes of the nucleon

critically on the Λ_{QCD} parameter. Specifically,

$$\alpha_S \propto 1/\ln(Q^2/\Lambda^2_{QCD}) \tag{2}$$

where $Q^2 = 4$ times the square of the invariant mass of a particle mediating the interaction, with the consequence that

$$M_X \propto \Lambda_{QCD}. \tag{3}$$

Weinberg [2] has reported a dependence for M_X given by

$$M_X = 1.5 \times 10^{15} \Lambda_{QCD} \text{ GeV}. \tag{4}$$

Taking a value for $\Lambda_{QCD} = 300$ MeV, this value of M_X yields a corresponding value of τ_N:

$$\tau_N = 10^{31 \pm 1} \text{ years}. \tag{5}$$

Branching ratios for the proton and neutron decay modes have been predicted using SU_6 quark models and bag models and the conclusions that one can easily draw from these predictions is that for Cabibbo-favored modes, the decays $p \to e^+\pi^0$ and $n \to e^+\pi^-$ are dominant (35% and 70% of their total rates, respectively) and the proton and neutron lifetimes are about equal.

3. *Basic experimental considerations*

In an experimental apparatus containing N_0 nucleons the observation of ΔN decays in a time interval Δt years yields a lifetime

$$t(\text{years}) = A \times \frac{N_0}{\Delta N/\Delta t} \tag{6}$$

where A is a factor proportional to the decay modes to which the apparatus is sensitive, the efficiency of the apparatus for detecting various decay modes and the data loss factors due to nuclear absorption of the decay products, event reconstruction losses, etc. If one optimistically takes $A = 1$ and observes *no* events over a period of observation of 1 year,

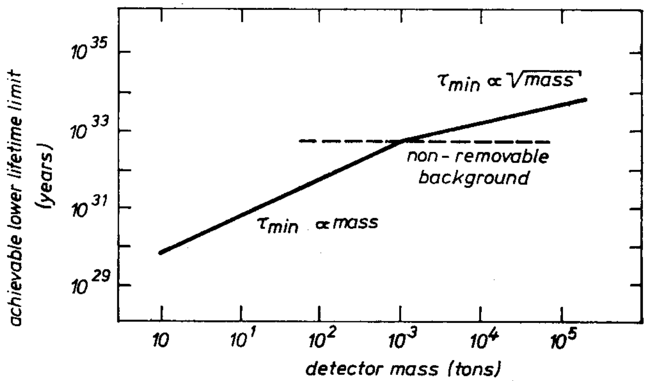

Fig. 2. Plot of achievable lower limit on the nucleon lifetime vs. detector mass. When the limit corresponds to the non-removable background level, further addition to the detector will increase the limit only as the square root of the additional mass

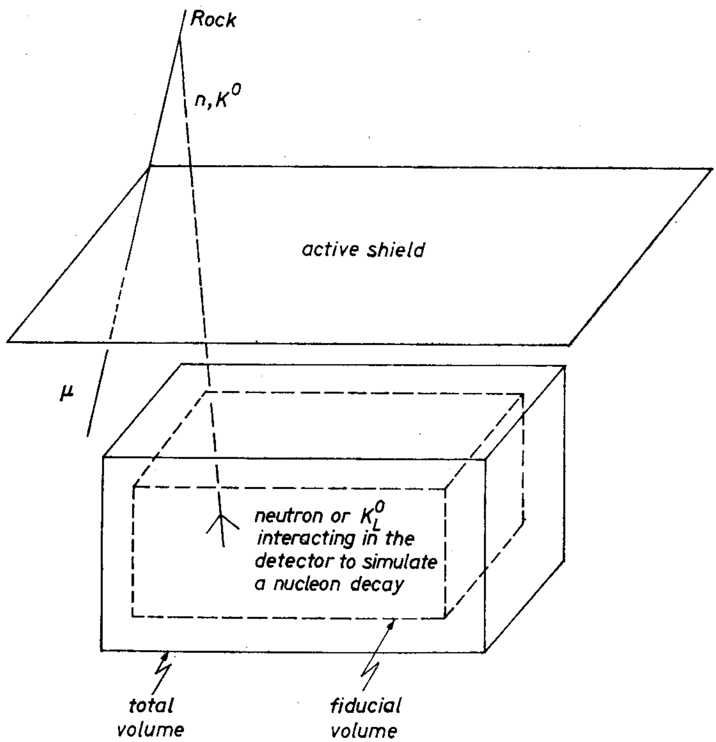

Fig. 3. A cosmic ray muon interacts in the rock above the detector, producing a neutral hadron which in turn simulates a nucleon decay event in the detector. The muon remains unobserved. An active shield above the detector can intercept the muon and veto the event

then $\tau \gtrsim N_0$, the number of nucleons present. The current published lower limit [3] on the nucleon lifetime is 10^{30} years and so future experiments must consists of detectors with masses well in excess of 10^{30} nucleons (1.6 tons).

Several considerations will affect the lower limit which a detector can place on the lifetime of the nucleon. Background events in the detector which are indistinguishable from nucleon decay place a practical upper limit on the size of the detector. Figure 2 is a plot of the achievable lower lifetime limit (in years) as a function of detector mass (in kilotons) which can be achieved in 1 year of observation. If in a 10^3 ton detector there occurs 1 background event/year which is inseparable from a nucleon decay event, then increasing the detector mass by another factor of 10 will yield 10 ± 3 such background events/year and so one claims that *at most* 3 of these events could have been nucleon decays. Hence, by equation (6) above, the lower lifetime limit is increased only by a factor of 3 by increasing the mass by a factor of 10. The largest detectors being installed or planned expect about 1 inseparable background event/year.

Backgrounds originate from two sources: 1) neutral hadrons (n, K^0) produced by cosmic ray muons in material (rock) outside of the detector enter the volume of the detector and interact, the muon remaining undetected and 2) neutrinos produced in the earth's

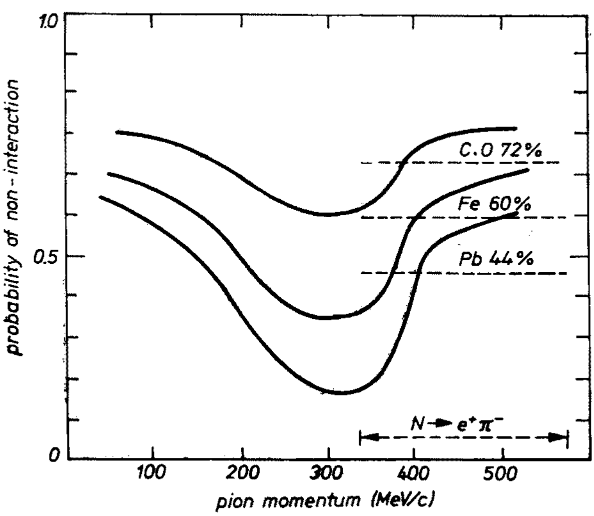

Fig. 4. Probability of non-interaction of pions in different nuclei as a function of pion momentum

atmosphere interact in the detector and can simulate a proton decay. Figure 3 is a sketch of background 1). This background can be reduced to an arbitrarily low level by performing the experiment sufficiently deep beneath the earth's surface and defining a fiducial volume within the physical detector such that the neutral hadron will not penetrate sufficiently far into the detector to enter the fiducial volume. Background 2) can only be removed in the data analysis.

Finally, there will be a loss of data due to the fact that such experiments are performed with either water or iron as the decaying material. A pion resulting from the decay $n \rightarrow e^+\pi^-$

can interact in the nucleus containing the original decaying nucleon and the event may then be lost. Figure 4 is the result of a Monte Carlo calculation [4] showing the fraction of events in which the pion emerges from the nucleus *without* interacting, as a function of pion momentum. The curves are presented for C, O, Fe and Pb. Because of the Fermi motion of a nucleon within the nucleus, the momentum of a pion resulting from a 2-body nucleon decay will not have a unique momentum but will have the range of momenta shown in Figure 4 (340–590 MeV/c). Hence, the average probability of non-interaction of the decay pion in iron is 60% corresponding to a 40% data loss. Actually, 40% represents an over-estimate because those pions that scatter elastically within the nucleus can emerge to produce an event which is topologically consistent with a free nucleon decay. A final point here is that because of the Fermi motion of a nucleon within a nucleus, a 2-body decay will in general not appear as an event in which the decay particles are colinear. Instead, there will be an angle between the pion and electron momentum vectors anywhere in the range 155° to 180°. The principal background which can simulate a two-body decay of the nucleon is an event in the detector corresponding to the reaction $\nu + p \rightarrow e + \pi^{\pm} + p$ where the e and π momentum vectors are nearly colinear (in the range 155° to 180°). In the largest detectors being planned there will be about 1 such event per year.

4. *Classification of experiments*

The experiments in progress or being planned fall into two major categories; 1) the water Cerenkov method and 2) the iron calorimeter method. In the water Cerenkov method an array of photomultiplier tubes is positioned either on the walls or throughout the volume of a large container filled with water. In the iron calorimeter method crossed planes of proportional or streamer tubes are embedded in a large volume of iron or iron oxide. The most ambitious of the iron calorimeter experiments [13] uses layers of flashtube

TABLE I

Comparison of water Cerenkov and fine grain calorimeter techniques. A single × denotes an advantage. A double × × denotes a decided advantage

Important properties	Water Cerenkov	Fine grain calorimeter
Energy Resolution for mode $p \rightarrow e^{+}\pi^{0}$	comparable (10–20%)	
Particle Identification		×
Pattern Recognition		× ×
Direction of Track	× ×	
Lower Pion Internal Reinteraction	×	
Low Energy Pion Detection		×
Highest Ratio of Fiducial to Total Mass		×
Ease of Constructing a Prototype		×
Speed of Construction	×	
Ability to Add Mass in Stages (modularity)		× ×
Experience with Technique		×
Cost per Kiloton of Mass	×	

TABLE II

Nucleon lifetime experiments in progress or being planned

Type	Collaboration	Total mass	Depth meters of water equiv.	Special features	Status (May, 1981)
Water Cerenkov Experiments	University of Pennsylvania [5]	150 tons	4400 m Gold Mine	Observes the delay coincidence between a stopping μ and its decay e in water Cerenkov tanks	Data $\tau \gtrsim 10^{30}$ years
	Michigan-Irvine Brookhaven [6]	6.8 kilotons	1600 m Salt Mine	2048 PM tubes paper the 6 walls of a tank of water	Excavation complete, installation in progress
	Harvard Purdue Wisconsin [7]	0.8 kiloton	1600 m Mine	704 PM tubes immersed throughout the volume of a large cylindrical tank of ,water	Installation in progress
	Tokyo [8]	3.4 kilotons	1300 m Mine	20 inch diameter PM tubes used to maximize the fraction of C γ's intercepted	Funded and under design
Calorimeter Experiments	Bombay Osaka Tokyo [9]	150 tons	7000 m Gold Mine	Iron proportional tubes of cross-sectional area $10 \times 10\ cm^2$ sandwiched between 1/2 inch thick iron plates	Data-three possible events
	Minnesota Argonne [10]	30 tons	1500 m Iron Mine	Proportional tubes embedded in a mixture of cement and iron oxide (taconite) mined in same mine	Under test
	Oxford (with above)	1 kiloton	1500 m Iron Mine	Drift chambers with glass as active mass	Proposed

Milan Turin Frascati CERN [11]	150 tons	5000 m Tunnel of Mont Blanc	1 cm × 1 cm streamer tubes made of resistive material and read out by external inductive strips	In fabrication and installation
Tokyo [12]	300 then 600 then 1200 tons	1000 m Tunnel	Flashtubes are made of sealed glass cylinders	Proposed
Orsay Palaiseau Saclay Wuppertal [13]	1.5 kilotons	4500 m Tunnel of Fréjus	Flashtube chambers made of PVC material, each filament has cross sectional area of 5×5 mm^2. Flashtubes read out electronically	Funded and under design

chambers sandwiched between thin (3 to 4 mm) sheets of iron with Geiger tubes providing the trigger. In Table I we compare the most important features of this "fine-grain" experiment with the largest of the water Cerenkov experiments [6].

5. *The experiments*

Table II is a tabulation of the experiments in progress or being planned. I will comment only on the two experiments which have presented preliminary data and then comment on the large European calorimeter experiment which will be installed in the tunnel of Fréjus.

1. The university of Pennsylvania experiment

An initial result has been presented by the University of Pennsylvania experiment [5] which is located in the Homestake mine in South Dakota. A sketch of the experiment is shown in Fig. 5. Tanks with photomultiplier tubes attached are filled with water and

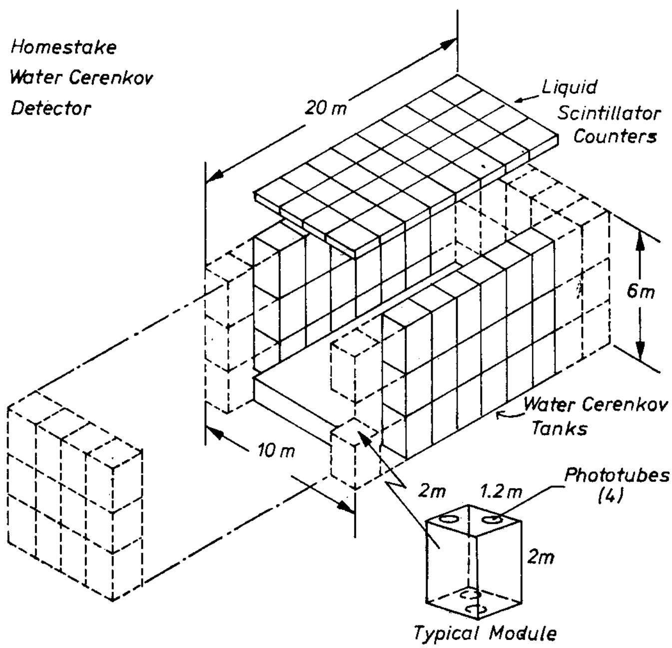

Fig. 5. The Homestake Water Cerenkov Detector. The portion of the detector with a solid outline is in operation. The dashed portion has not yet been installed. Not shown is the CCl_4 tank at the center of the apparatus used in the solar neutrino experiment

are stacked on either side ol the Davis solar neutrino CCl_4 tank. The fiducial mass of water equals 150 tons. Above and below the Davis CCl_4 tank are planes of liquid scintillator counters which serve to flag events in which a stopping μ and its subsequent decay into an electron occuring in the water Cerenkov tanks is accompanied by ionizing radiation traversing the liquid scintillator. Such events are not considered as candidates for nucleon decay. The geometric efficiencies of these counters, used as vetos is about 50%.

During a run of one year, 4 events were observed which contained a deposition of visible energy in the water Cerenkov tanks commensurate with the decay of a nucleon into a final state having a μ^+ with a subsequent decay into an e^+, e.g.,

$$N \to \mu^+ + X, \quad p \to e^+ + \varrho^0$$
$$\to e^+ \qquad\qquad \to \pi^+ + \pi^-$$
$$\to \mu^+ \to e^+, \text{ etc.}$$

One of the four events was accompanied by a signal in the liquid scintillator veto counters reducing the number of candidates to 3 ± 2. Since the geometric efficiency of the veto counters is about 50%, one would expect that an additional event should have been accompanied by a veto signal, or, subtracting a background of 1 ± 1 from the signal of 3 ± 2, one obtains a corrected signal of 2 ± 2 events. The experimenters conservatively wish to use this number as an upper limit on the number of decays observed. Assuming a product of the branching ratio into final states which can yield a μ^+ times the detection efficiency of the apparatus equal to 5%, the experimenters obtain a lower limit on the lifetime, based on two events, equal to

$$\tau \gtrsim 10^{30} \text{ years.}$$

2. Tata Institute – Osaka University Experiment

An interesting preliminary result has been presented [9] by these experimenters in which 3 events that are difficult to attribute to standard background sources have been observed in their detector. Located in a deep mine in the Kolar Gold Field, the detector consists of crossed planes of proportional tubes, each plane of which is separated from the adjacent planes by a 1/2 inch thickness of iron. The total mass is 150 tons and the fiducial mass is 100 tons. Figure 6 shows the two views of one of these events which is consistent with the decay $p \to e^+\pi^0$ in which one of the γ's from the π^0 takes practically all of the energy of the π^0. As is the case with the other two events not shown here, one of the tracks leaves the detector and so it is not possible to obtain a value for the total visible energy associated with the event. There appear to be gaps along the tracks corresponding to proportional tubes that did not fire. The proportional tubes marked "X" were not operative and the remainder of the tubes that did not fire along the particle paths corresponds to locations along the shower development of either the e or γ in which there may have been no ionizing radiation (electrons) but just γ's. Since the cross-sectional area of each of the proportional tubes is 10×10 cm^2, and since the *maximum* transverse dimension of a several hundred MeV electron shower is about 10 cm, an electron or photon in this detector will always appear as a singly-ionizing particle passing through the detector. Although the experimenters claim to have pulse height information on each of the proportional tubes, this information is not available at this time.

The experimenters have qualified these three events by the caveat that if they are *not* nucleon decay, then they correspond to background events which are not understood.

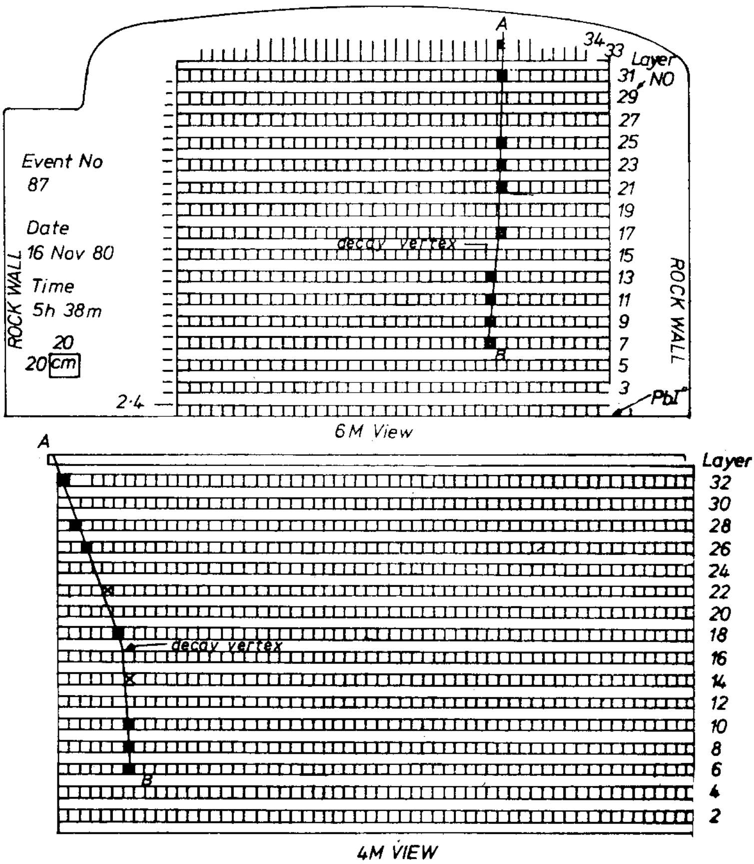

Fig. 6. A nucleon decay candidate in the Tata Institute–Osaka University experiment. Proportional tubes marked X are not functioning. Track A is seen to leave the top of the detector, making an energy determination of this event impossible

If these events do indeed correspond to nucleon decay, the experimenters offer the following computation of the nucleon lifetime:

Assume that the product of the branching ratios to which the detector is sensitive times the detection efficiency equals 0.5. Also, assume that the pion absorption by the nucleus is offset by a "life-shortening" factor associated with the nucleon emitting a virtual pion in the nucleus which then scatters from an adjacent nucleon to produce a real pion (or pions). These factors combined give a value for A in equation (6) above equal to 0.5. With an observation time equal to 131 days, the experimenters obtain a lifetime value

$$\tau = 3.5 \times 10^{30} \text{ years.}$$

3. The Orsay–Palaiseau–Saclay–Wuppertal Experiment [13]

This experiment is mentioned here because it is the most ambitious of the "second generation" calorimeter experiments and represents a considerable refinement over, for example, the Tata Institute–Osaka University experiment discussed above. The Orsay–

–Palaiseau–Saclay–Wuppertal experiment is planned for 1.5 kilotons and will be installed beginning in 1982 in the tunnel of Fréjus, a new alpine tunnel connecting Modane, France with Bardonecchia, Italy.

The detector will employ the plastic flashtube chamber technique [14] in which planes of plastic flashtube material, illustrated in figure 7, are sandwiched between thin (3–4 mm)

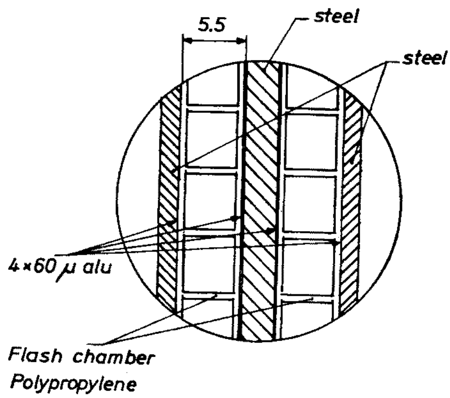

Fig. 7. A detail of an element of the Orsay–Palaiseau–Saclay experiment. The flashtube chamber planes are sandwiched between thin sheets of iron. Also shown are the aluminum electrodes on the outside surfaces of a plastic flashtube sheet across which the high voltage pulse is applied

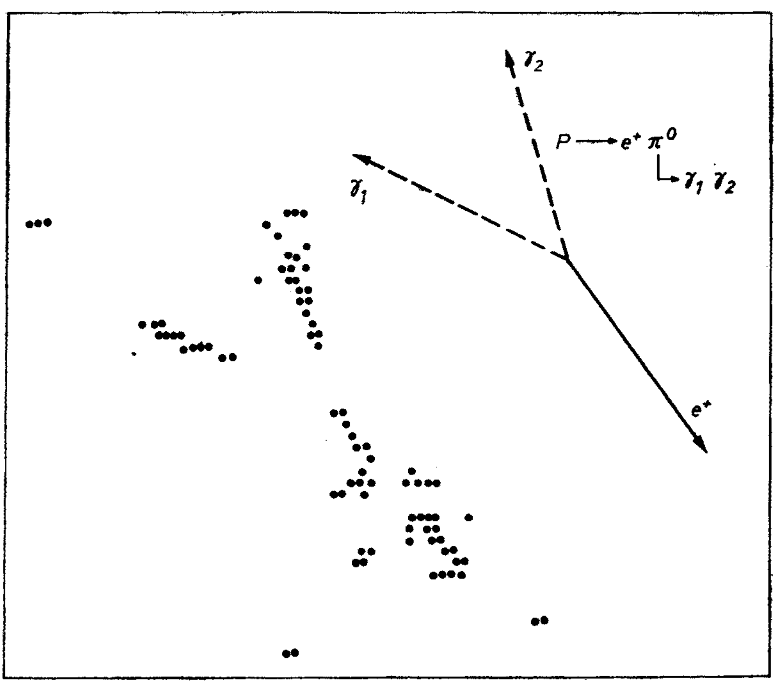

Fig. 8. A Monte Carlo simulation of an event of the type $p \to e^+\pi^0$ in the Orsay–Palaiseau-Saclay calorimeter. The total energy of this kind of event can be determined to 10%

sheets of iron. The flashtube chamber technique is now well understood. In short, a particle traversing a flashtube will cause a plasma to form in the noble gas which fills the tube by means of a high voltage pulse applied to the entire flashtube plane immediately after the traversal of the ionizing particle. Each tube will be read out electronically by means of an electrode either external (capacitive coupling) or internal to the tube. The calorimeter trigger will be provided by the use of planes of Geiger tubes (not shown in figure 7).

Figure 8 shows a Monte Carlo simulation of an event of the type $p \to e^+\pi^0$. The energy determination for this decay mode will be about 10%. This detector is particularly well-suited for the study of decay modes having a large number of particles in the final state. This feature becomes important when trying to establish whether a nucleon decays by $\Delta B = \Delta L$ transitions or by $\Delta B = 2$ transitions in the nucleus. The latter kind of decay would have the characteristic appearance of a $\bar{p}p$ annihilation. Perhaps both kinds of transitions take place in nature. In order to relate the experiments which are studying $n \to \bar{n}$ oscillations to $\Delta B = 2$ transitions in the nucleus, a detector of this sort will be very useful.

6. *Conclusions*

Both theoretical estimates and preliminary experimental results point towards a nucleon lifetime of perhaps less than 10^{31} years. Next year's 5th Warsaw Symposium should be able to provide a larger number of = signs when quoting the nucleon lifetime and fewer $\geqslant$ signs as is the case this year, since several additional experiments will become operational during the present year, 1981.

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