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MASTER

BARYON CONSERVATION (Experiments)

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The organizers of this conference were perhaps subconsciously aware that the discussion of proton stability started at about the same time as the concept of the neutrino, 50 years ago. During most of the half century since Weyl, Stückelberg and Wigner first postulated proton stability, nearly everybody believed in it as an absolute truth.[1]

About a quarter of a century after Weyl we realized that proton stability is an empirical question and asked: "Is the proton really stable?" Of course, experimentally we cannot prove absolute stability. But we can at least give quantitative limits of stability or find the actual decay of the proton. This was our attitude. By now everybody has gotten used to the idea that so-called "elementary particles" can decay, but I still remember the shock I felt when we found at the Cavendish in 1934 that the free neutron weighed definitely more than the hydrogen atom and that it therefore should decay by β emission with a half life which we then could estimate roughly from β-decay systematics to be about half an hour. In order to avoid confusion with the β-decay of the neutron when we talk of nucleon decay I shall usually use proton decay as a generic term by which I often mean to include the decay of neutrons which have been stabilized against β-decay by nuclear binding.

The first results on limits for proton stability were obtained in 1954:[2] two methods were discussed, a nuclear method and a counting method. The nuclear method permits us to obtain a lifetime limit for a nucleon because of the fact that nuclear shells exist. Only rarely, if one of the loosely bound nucleons would decay, would the nucleus be left unexcited. Usually some

excitation energy is left in the nucleus which leads to a de-excitation which can be detected in various ways. The mode of de-excitation which we considered at first was induced fission which would look like spontaneous fission. Since spontaneous fission had been looked for in thorium but not found, we could give a limit for nucleon decay of $\sim 10^{20}$ y. The best limit for spontaneous fission of ^{232}Th was obtained later by Flerov. If we multiply his limit by $\sim$200, the approximate number of particles in Th, we get an approximate limit for nucleon decay of $\sim 2 \times 10^{22}$ y. To a very high approximation it would not matter how the nucleon decays. For instance, if a neutron would decay into three neutrinos which could be described as "disappeared without a trace", it would still leave a hole behind which is equivalent to a high average nuclear excitation and this would lead to fission.

The nuclear method was extended by Peter Rosen[3] who proposed the use of more versatile radiochemical methods. Essentially one uses the fact that an excited nucleus resulting from proton decay can emit 0, 1, 2, ... nucleons and one can calculate the relative probabilities roughly from the shell model. For instance, in ^{130}Te the decay of a neutron, if it does not leave the nucleus too highly excited, will lead to ^{129}Te which decays into ^{129}I and ultimately into ^{129}Xe. Typically the early experimental results were all parasitic, i.e., the experiments were originally done for different reasons. In this case people were interested in double-β- decay and looked for ^{132}Xe from the isotope ^{132}Te. They also got limits on ^{129}Xe and from this Evans and Steinberg[4] deduced a limit of 1.6×10^{25} y, again independent of the decay mode. And then Fireman, et al,[5] and Steinberg et al[5] in 1977 did a deliberate or "dedicated" experiment. They had a large amount of potassium where the ^{39}K can, after the decay of one nucleon and the loss of another one, ultimately end up as ^{37}Ar, for which there are very sensitive methods of detection developed by Ray Davis. They obtained a limit for nucleon decay $>2.2 \times 10^{26}$ y. Thus nuclear methods have gone from $\sim 10^{20}$ to $\sim 10^{26}$y. The counting methods in which certain charged particles of some minimum energy are detected were largely pursued by Reines and his collaborators and have reached $\sim 10^{30}$ y as a limit for nucleon decay.[6]

There is a proposal for a nuclear method which might go well beyond 10^{26} y, but it is a difficult one. It is due to Charles Bennett of Princeton University who takes samples of mica from a deep mine so that they have not been exposed to too many cosmic rays. If a nucleon were to decay, π mesons would be emitted sometime and reabsorbed in the nucleus leading to spallation. The spallation gives heavier tracks which etching brings out and these etched tracks can then be counted. It is very laborious; he has now samples from fairly deep down and he thinks in principle if he gets very old samples he could reach lifetimes close to those obtained by the present counting methods. This is

probably somewhat optimistic but it is interesting that methods which are independent of decay modes may go pretty far.

If Weyl had asked himself how can a proton decay, he would not have been able to write down a single equation conserving charge, energy, spin and momentum because he speculated on proton conservation before the positron was discovered. But look at the embarrassment of riches which we have now. Fig. 1 shows all the known particles whose masses are below that of a nucleon. (I hope you will forgive me for not putting the neutrino masses at their "correct" place.) Therefore in principle the nucleon could decay in many ways, involving at least one fermion to conserve spin, and one or more other particles. Of course proton decay could only happen if the charges of, say, the proton and the π^+ were exactly equal because otherwise charge conservation alone would stop it.[7] On the other hand, if we ever find nucleon decay then we could conclude that the charges are equal. The present limits for the differences between π and nucleon charges, or positron and nucleon charges, etc., are of the order of 10^{-19} of an electron charge.

While it is against my taste to talk of experiments in the future tense, it is unavoidable in this field. I shall therefore now talk about the experiments which are either in progress or planned. It is a very laborious task because proposals, some tentative, have been reaching me in a haphazard manner, mostly in the last few days, some only this afternoon, and so I hope you forgive me if it is not perfectly organized. Until very recently most experiments were parasitic to neutrino experiments for the very simple reason that to detect neutrinos with their small cross sections people built very massive counters and such counters can also be useful for the very long lifetime looked for in proton decay. Just as an illustration, one ton of matter, say, has roughly 10^{30} nucleons, so if the lifetime of the proton were 10^{30} years only one would decay per year in a ton of matter and therefore to push this limit much further one needs many tons of matter. In the United States there are four different attempts to measure the proton lifetime in progress. I shall talk first about these and then tell you of plans outside the United States. Dr. Miyake will talk later in detail about an Indian-Japanese collaborative effort which is in progress. Now why do we all make this effort at this time? While the older generation of theoretical physicists felt it in their bones that the proton is stable, the younger generation has a visceral feeling that it decays, as we have just heard from Professor Pati.

The lifetimes which are predicted by the Grand Unified Theories (GUTS) are very seductively close to the old experimental limit and it looks as if just a little extra effort should bring us to the promised land. So, very many groups are now in the

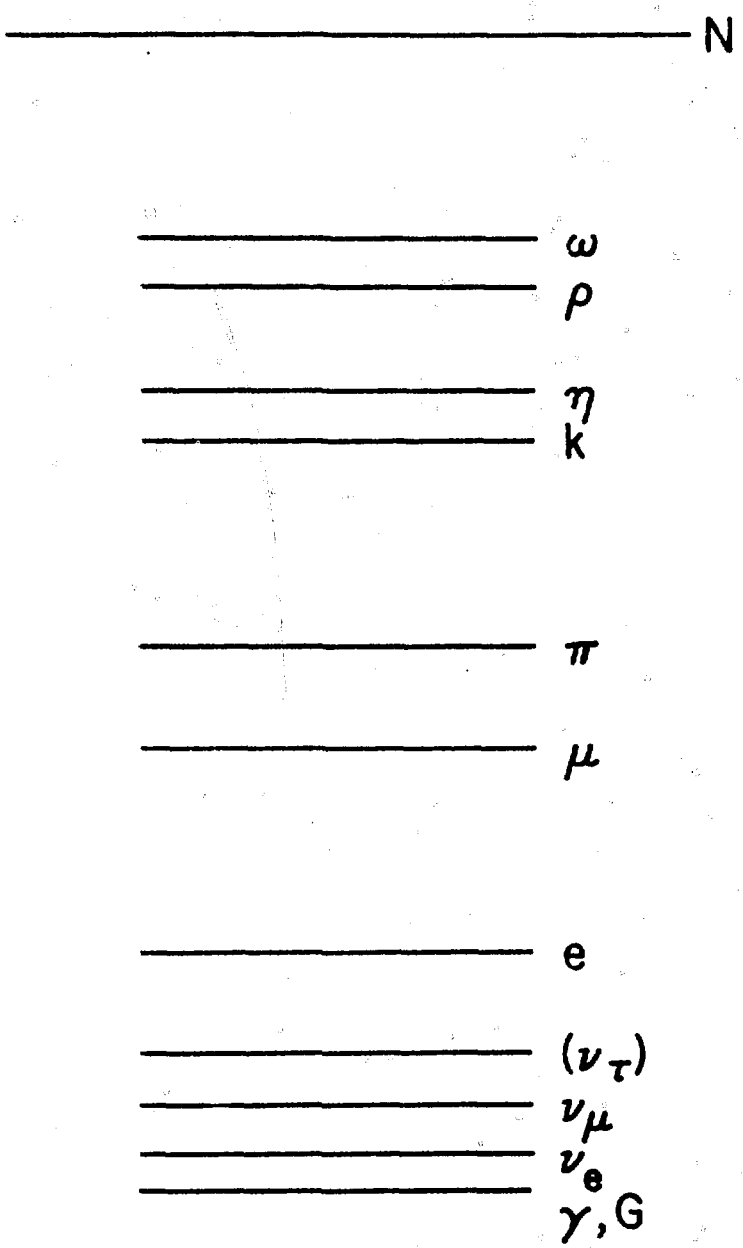

Fig. 1. Schematic presentation of particles of mass lower than that of a nucleon.

process of preparing or proposing experiments, and for the first time instead of being parasitic to neutrino experiments these proposed experiments are dedicated to proton decay studies, and by being dedicated they emphasize sometimes a different technique than one most useful in neutrino research. But of course the situation is immediately turned around: as soon as you build these very large counters there are many new neutrino ideas which have to be tested and the neutrino becomes parasitic to the proton, so let us perhaps drop this nasty word and say from now on that these experiments will be often symbiotic.

I hope you will forgive me if I start out with the experiment I am best acquainted with, the one with which I am connected, the Irvine-Michigan-Brookhaven search for proton decay. We tried to find a place where it would not be too expensive to dig a very large hole because we wanted to do an experiment with a sufficient amount of material that we could test some of the predictions for the proton lifetime, e.g., those based on SU(5) and related higher groups which predict lifetimes well below 10^{33} y. We hope to do an experiment which can reach, or very closely reach, this limit. The place we chose was one known to Reines and collaborators for a long time. It is a salt mine in Fairport Harbor, Ohio, not far from Cleveland, and it is a place where Mary K. Gaillard comes from, a good omen!

If one wants to use a very large amount of material at a reasonable cost, water seems a good choice. We intend to use Čerenkov radiation from water. If a proton decays, the energetic particles would produce Čerenkov radiation and if we can detect the radiation efficiently, and if we can reconstruct the events, then we should be able, by using several thousand tons of water, to reach the present theoretical limits.

The Čerenkov spectrum in water decreases steeply as the wavelength increases, but the ultraviolet part gets very rapidly absorbed in water, leaving only the visible part of the spectrum and therefore some people are using a different method, a wave shifter, which shifts the ultraviolet part of the spectrum to the visible where the water does not absorb appreciably, and where the phototubes can detect it easily. We chose instead to stay with the Čerenkov radiation alone because we believe we can in this way define the positions better.

After 10 meters of water the Čerenkov light left is essentially in the visible region where water is very transparent. The mean free path at the maximum transmission (~300 nanometers) is over 40 meters in pure water. Our phototubes have a wavelength sensitivity which matches the surviving photon spectrum closely.

To test the ideas, a water tank was built which has a 10-meter baseline. It was built at Michigan University and tested by some members of our group there. The test is made by allowing a coincidence between a cosmic ray μ meson traversing the water (defined by a coincidence between two counters) and phototubes recording Čerenkov radiation from the μ meson. We could predict 2.5 photoelectrons at 35 feet. Actually three photoelectrons were seen. The water was carefully purified and the amount of water circulating per unit time was scaled so that we should be able to achieve the same kind of purification for the large volume of water to be used in the final arrangement. The big hole which had to be dug at the mine is now essentially finished.

Our plans were discussed in detail at the Bergen ν '79 meeting.[8]

We believe we can take care of backgrounds by using just the inner part of the water cube as the fiducial volume, with the outer part as a sort of anticoincidence by software, except that one cannot stop neutrinos from initiating, inside the fiducial volume, events which might sometime mimic proton decay. It was therefore very important that the results of a Gargamelle neutrino experiment, where the PS neutrinos had roughly the same spectrum as the atmospheric ones, were made available to us through the kindness of G. Martin and M. Pohl. We therefore expect in two years of running only about one background count due to the neutrinos simulating a proton decay. That would correspond to a limit close to 10^{33} y.

The digging in the salt mine was done by a continuous digger which has been developed by an English company called DOSCO. At present the hole is being prepared for the final putting down of the floor and then we will install a liner to hold the water. We hope that by late spring of next year, barring the usual holdups or lack of money, etc., we can start taking data.

One experimental effort by a University of Pennsylvania group[9] is getting data right now; this was due to the happy circumstance that they built some time ago a neutrino detector in the Homestake Mine where Ray Davis' chlorine detector is located. In fact their detector surrounds his solar neutrino detector. The Pennsylvania neutrino detector has symbiotically developed into a proton decay detector. They use wavelength shifters and look for μ-e decay, where a μ^+ could either be created directly from proton decay or indirectly as a decay product of the presumably more copious π^+'s. To reduce the data they use some theoretical branching ratio predictions.

They believe from a Monte Carlo study of the energy distribution of events expected from decays which lead to μ-e decay that none of their observed candidates are due to proton decay and therefore they can give a limit of $\gtrsim 2 \times 10^{30}$ y for the proton lifetime. They will now go from about 150 tons to 500 tons of water and hope to push the limit to $\sim 10^{31}$ y.

The Harvard-Purdue-Wisconsin Group[10] is building a one kiloton water detector in an old silver mine in Park City, Utah, which is the place where Keuffel and his group used to do their cosmic ray research. It has a depth of 1800 meter water equivalent; they also use a water Čerenkov counter, but with a wavelength shifter and they distribute their phototubes throughout the counter volume. In this way they will obtain good energy resolution.

A University of Minnesota group uses an old iron mine at Soudan, Minnesota.[11] They use very cheap counters which can be built in small units and as more money becomes available they can build more and more units. They make gas proportional counters from simple steel tubes embedded in ferro-concrete which they get cheaply and the first modules are in the mine. They want at first to build a 45-ton detector to just check the ideas. They expect to be able to recognize a number of different decay modes.

Tables 1 - 7 on planned proton lifetime experiments are based on questionnaires filled out for this conference by a number of research groups planning proton lifetime experiments outside the United States.

Recently there has been a renewed interest in n-$\bar{n}$ oscillations.[12] An experiment will soon start at the Laue-Langevin Center at Grenoble[13] and another is being proposed for Oak Ridge.[14]

Table 1. P Lifetime Experiments

Collaborative Institutions	Frascati-Milano-Torino plus support from CERN (1st Generation Experiment)
Location	Mont Blanc Tunnel (Garage 17)
Depth	> 5000 metres of w.e.
Weight of Detector	150 tons
Method of Detection	1 cm iron plates interleaved with limited streamer tubes
(Partial) p Lifetime Limits Obtainable	10^{31} - 10^{32} y depending on length of the run
Present Status and/or Time when (Preliminary) Results are Expected	Experiment in preparation. First data end of 1981. Exposure to neutrinos from unfocused 10 GeV protons at CERN.

Table 2. P Lifetime Experiments

Collaborative Institutions	Frascati-Milano-Rome-Torino (2nd Generation Experiment)
Location	In Fréjus or other European Tunnels
Depth	$\sim$ 4000 m(w.e.)
Weight of Detector	A few kilotons
Method of Detection	Fine grain calorimeter
(Partial) p Lifetime Limits Obtainable	10^{32} - 10^{33} y depending on length of the run
Present Status and/or Time when (Preliminary) Results are Expected	Letter of Intent to the Italian authorities.

Table 3. P Lifetime Experiments

Collaborative Institutions	Orsay-Ecole Polytechnique-Saclay, plus Italian Groups
Location	Fréjus Tunnel
Depth	$\sim$ 4000 m(w.e.)
Weight of Detector	2 kilotons at start
Method of Detection	Calorimetry with 4mm section flash tubes plus Fe (3mm); Possibly C in H_2O
(Partial) p Lifetime Limits Obtainable	$\sim 10^{32}$ y
Present Status and/or Time when (Preliminary) Results are Expected	Negotiation on excavation on possible Franco-Italian laboratory in the Fréjus Tunnel, and tests on 5m long, 4 mm cross section plastic flash chambers.

Table 4. P Lifetime Experiments

Collaborative Institutions	Istituto di Cosmo-Geofisica del CNR - Torino Institute for Nuclear Research-Moscow Laboratori Nazional Frascati - INFN - Frascati
Location	Laboratory of the Mt. Blanc Tunnel
Depth	∿ 4,270 m(w.e.)
Weight of Detector	∿ 60 tons of Liquid Scint. ∿ 40 tons of Iron
Method of Detection	Liquid scintillator detection and anticoincidence system } 100 Tons
(Partial) p Lifetime Limits Obtainable	5×10^{31} y
Present Status and/or Time when (Preliminary) Results are Expected	End of 1981 (20 tons are running at present).

Table 5. P Lifetime Experiments

Collaborative Institutions	Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow
Location	Salt mine, Artyemorsk, Ukraine
Depth	∿ 600 m(w.e.)
Weight of Detector	100 ton liquid scintillator, surrounded by ∿ 200 ton liquid scintillator anticoincidence.
Method of Detection	Liquid scintillator 128 PM-tubes
(Partial) p Lifetime Limits Obtainable	10^{31} years?
Present Status and/or Time when (Preliminary) Results are Expected	Only projected so far.

Table 6. P Lifetime Experiments

Collaborative Institutions	Institute for Nuclear Research of Academy of Sciences of the USSR, Moscow
Location	Baksan Valley, North Caucasus
Depth	∿ 850 m(w.e.)
Weight of Detector	80 tons of liquid scintillator 220 tons of l.s. anticoincidence shield
Method of Detection	1200 liq. sc. detectors (Internal part of Baksan scintillator telescope)
(Partial) p Lifetime Limits Obtainable	For leading to μ-e decay only ∿ 5 x 10^{30} years
Present Status and/or Time when (Preliminary) Results are Expected	Starting from 1 July 1980. The beginning of 1981.

Table 7. P Lifetime Experiments

Collaborative Institutions	Tata Institute of Fundamental Research, Bombay, India Osaka City University, Osaka, Japan and ICR, University of Tokyo
Location	Kolar Gold Field, South India
Depth	$\sim$ 7600 m(w.e.)
Weight of Detector	150 tons. Fiducial volume $\sim$ 100 tons.
Method of Detection	PR counter array in crossed geometry
(Partial) p Lifetime Limits Obtainable	$\sim 10^{31}$ y
Present Status and/or Time when (Preliminary) Results are Expected	Within this year.

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