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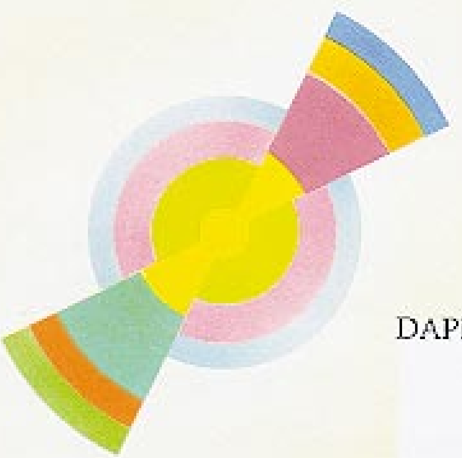

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BARYON INSTABILITY SEARCH: PRESENT STATUS AND FUTURE PERSPECTIVES

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BARYON INSTABILITY SEARCH: PRESENT STATUS AND FUTURE PERSPECTIVES

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ABSTRACT

Nucleon decay appears as a consequence of models trying to explain the baryon-antibaryon asymmetry. This has motivated 15 years ago many underground experiments devoted to the search of proton and neutron decay. A very large number of decay channels have been investigated and no evidence has been found yielding lower limits on lifetime which rule out the minimal SU(5) Grand Unified Theory predictions and put severe constraints on more complicated models.

Next generation experiments like Super-Kamiokande, which is starting to take data now, ICARUS, whose a 600 ton prototype is under construction, will be sensitive to more complicated models predicting larger lifetimes.

1. Introduction

During its early story the Universe was dominated by radiations and baryon-antibaryon pairs were continuously created and annihilated. The annihilation rate decreased with the expanding Universe because the probability that nucleons and antinucleons could find each other decreased. So, it is natural to ask what is the mechanism which allows the observed asymmetry between baryons and antibaryons at least at the galactic scale.

The hypothesis that the large asymmetry observed today is the relic of a small statistical fluctuation at the epoch when $N_N \approx N_{\overline{N}} \approx N_\gamma$ is excluded [1] because the present ratio N_N/N_γ is of the order of 10^{-10} and the present number of nucleons in the Galaxy is $\approx 10^{69}$ $(10^{12} M_\odot)$. So, the number of nucleons and antinucleons was 10^{79} before 10^{-6} s after the bang in the same co-moving volume allowing only a 10^{-40} relative statistical fluctuation which would be 30 orders of magnitude lower than what observed.

In 1967 A. D. Sakharov [2] suggested that the simultaneous effects of B-violating interactions, C and CP violation, and departure from thermal equilibrium could produce a small baryon-antibaryon asymmetry which, after baryon-antibaryon annihilations, would produce the asymmetry observed today with a nucleon density $N_N/N_\gamma \approx 10^{-10}$.

Models allowing B-violating interactions have been developed in the framework of Grand Unified Theories (GUT) that unify strong and electroweak interactions. In these models quarks, antiquarks, and leptons are members of the same representations and, thus, there exist gauge bosons that allow B-violating transitions between quarks and antiquarks or leptons. Unlike what happens at low energy the cross section for B-violating scattering of fermions was not suppressed relative to other interactions when the temperature was greater than the mass of the gauge boson.

A fundamental consequence is that, if some mechanisms violating the baryon conservation exist, one can expect that the nucleon is unstable. The simplest model is the minimal SU(5) GUT [3] which predicts a proton lifetime between 10^{28} and 10^{31} years. Its supersymmetric extension [4] predicts that the dominant channel in proton decay is $p \to \overline{\nu}_\mu K^+$. As it will discussed below the first model is excluded by experiments searching for nucleon decay. Moreover it has been demonstrated that these models cannot explain the present baryon-antibaryon asymmetry [1].

Different schemes have been proposed [5] like dinucleon decays in nuclei ($NN \to Nl^+ + \cdots$), virtual meson exchanges ($pn \to l^+\overline{\nu}_l$) and models violating $B-L$ ($N \to l +$ mesons). The possible decay modes are summarized in table 1 for channels which may be detected in underground experiments.

Table 1. Schematic description of different visible nucleon decay modes for different ΔB and $\Delta(B-L)$ values. M represents a "mesonic" system of particles (i.e. a system with $B = L = 0$).

	$\Delta(B-L)=0$	$\Delta(B-L)=2$
$\Delta B = 1$	$N \to \bar{l}M$ $N \to \bar{l}\,\bar{l}\,l$ $NN \to l^+N$	$N \to lM$ $N \to l\,l\,\bar{l}$ $NN \to l^-N$
$\Delta B = 2$	$pp \to l^+l^+$ $pn \to l^+\overline{\nu}$	$NN \to MM$ $pn \to l^+\nu$ $nn \to l^+l^-$

2. The experiments

Among seven experiments [6–12] devoted to the nucleon decay searches listed in table 2, three were Čerenkov devices and four were ionization tracking calorimeters.

Table 2. Major characteristics of different underground experiments.

Experiment	technique	Total mass (Tons)	Fiducial mass (Tons)	Depth (m.w.e.)
IMB	Water Č	6900	3000	1600
HPW	Water Č	700	150	1500
KAMIOKANDE	Water Č	4500	1000	2700
KGF	Tracking cal.	140	60	7600
NUSEX	Tracking cal.	150	100	5100
Fréjus	Tracking cal.	912	550	4700
Soudan II	Tracking cal.	963	800	2100

The principle of the search of nucleon decay candidates is based on the selection of fully-contained events with energy-momentum balance compatible with the nucleon decay hypothesis. For this purpose only events with the primary vertex inside the fiducial volume and with all secondary tracks stopping inside the detector are selected. The energy of each track is estimated. The final selection consists in rejecting all events but those for which the sum of energies of all detected secondary particles (visible energy) and the sum of their momenta (visible momentum) are compatible with what is expected for the nucleon decay hypothesis.

3. Experimental method

The method used to estimate the nucleon lifetime consists in searching for a signal and in correcting it to take into account of the background contamination and of the detection efficiency.

3.1. Efficiency estimate

In order to calculate the detection efficiency a Monte Carlo simulation is used. Nucleon decays are generated inside the nuclei. The secondary particles are propagated in the nuclear matter by taking into account nuclear effects such as elastic scattering, charge exchange interactions and absorption. Effects due to the reinteraction inside the nucleus involving nucleons which are off their mass shell and due to the Fermi motion of the nuclear matter are also taken into account.

Particles leaving the nuclei are tracked in the detector and their interactions with the detector matter are simulated. The detector response is treated with the same algorithm as real data.

The analysis of simulated events allows to define the selection cuts on the visible energy and on the visible momentum. The overall detection efficiency is calculated as the ratio of the number of accepted events to the number of simulated events.

3.2. Background calculation

It is well known that the main source of background is atmospheric neutrinos interactions in the detector. In principle these events are characterized by a $E_{\rm vis} - \mid \vec{P}_{\rm vis} \mid$ balance, where $E_{\rm vis}$ and $\mid \vec{P}_{\rm vis} \mid$ are the visible energy and momentum and M_N is the nucleon mass, incompatible with the nucleon decay hypothesis. Nevertheless, nuclear effects and Fermi motion of the target nucleon may degrade the energy-momentum balance in such a way that several neutrino interactions may simulate nucleon decays. In order to calculate this contamination a Monte Carlo technique is used to simulate the νN interactions. The detector response to secondary particles is simulated as described for the efficiency calculations. The contamination of each nucleon decay channel is then estimated by taking into account the number of events which are selected by using the same topological and kinematical selection criteria as for nucleon decay events. The contamination is given by $N_B = N_{\rm sel} S_{\rm exp} / S_{\rm MC}$ where $N_{\rm sel}$ is the number of selected events, $S_{\rm exp}$ and $S_{\rm MC}$ are the exposures (in $\mathrm{kt} \cdot y$) used respectively for the real data and for the simulated atmospheric neutrinos interactions.

3.3. Calculation of the nucleon lifetime

A large number of decay channels has been investigated by different experiments [6–12]. For all channels no significant excess of events has been found and, thus, lower limits on the nucleon lifetime have been estimated for each channel.

The method of this calculation is based on the search of the upper limit at 90% of confidence level on the signal S_0 by taking into account othe number of selected candidates, the estimated background and corrections for the efficiency and for branching fractions of mesons in the final state.

The branching fraction of each nucleon decay studied is unknown. So, only limits on the ratio of the nucleon lifetime τ_N to the branching fraction BR are given. Its expression is:

$$\frac{\tau_N}{BR} = \frac{N_N M T}{S_0}$$

where N_N is the number of protons or neutrons per mass unit, M is the mass of the fiducial volume and T is the operating time.

4. Present status

A very large number of decay channels has been explored by underground experiments up to 1994. Since this date no new results have been published in this field.

All results are reported in the "Review of Particle Properties" published in 1994 [13] and are summarized in table 3.

Table 3. Ranges of nucleon lifetime lower limits for different type of decay channels.

	$\Delta(B-L)=0$	
$\Delta B=1$	$N \to \bar{l}M$	$10^{31}-10^{33}y$
	$N \to \bar{l}\bar{l}l$	$6\cdot10^{30}-6\cdot10^{32}y$
	$NN \to l^{+}N$	$2\cdot10^{31}-10^{32}y$
$\Delta B=2$	$pN \to l^{+}\bar{l}$	$1.6\cdot10^{30}-5.8\cdot10^{30}y$
	$\Delta(B-L)=2$	
$\Delta B=1$	$N \to lM$	$5\cdot10^{30}-5.5\cdot10^{31}y$
	$N \to ll\bar{l}$	$5\cdot10^{30}-7.4\cdot10^{31}y$
$\Delta B=2$	$NN \to MM$	$5\cdot10^{29}-3.4\cdot10^{30}y$
	$NN \to l\bar{l}$	$9\cdot10^{29}-5.8\cdot10^{30}y$

Clearly limits obtained for channels characterized by $\Delta B=1$ with $\Delta(B-L)=0$ are sufficiently constraining to rule out the minimal SU(5) GUT. Othe model which benefit of larger degrees of freedom, like the supersymmetric extension of SU(5) and models capable to explain the $B-\overline{B}$ asymmetry are also well constrained but not completely ruled out. The lower lifetime limit for the dominant SuSy channel, $p \to K^{+}\overline{\nu}_{\mu}$, is 10^{32} years.

In order to reach more severe constraints more massive detectors are under construction or in project.

5. Future perspectives

The Super-Kamiokande detector has started to operate in March, 1996 [14]. The total mass is 50 000 tons and the fiducial mass will probably be 30 000 tons. The Čerenkov light is collected by 11 146 PMTs with 20" photocathode diameter. The total photocathode area is 40% of the total walls area doubling the light collection efficiency compared to the Kamiokande detector.

Lifetime limits will be improved by a factor 5-20 and the limit of 10^{34} years will be reached for $p \to e^+\pi^0$.

Afterwards, the ICARUS project [15, 16] will achieve a significant improvement on the background rejection. Its 5 000 tons version will explore the region between 10^{33} and 10^{34} years in 5 years equivalent running time. A 600 tons prototype is under construction [16, 17]. This detector will be able to reach lifetime limits comparable to what obtained by the present experiments and will improve by an order of magnitude the limits for exotic channels.

Looking futher in the future, the only way to explore lifetimes above 10^{34} years is to use a detector containing 10^{35} to 10^{36} nucleons which corresponds to several hundreds of ktons. With the present technologies only a Čerenkov detector can be considered with several 100 000 PMTs for a cost of several 100 M$. It is clear that, due to financial and technological considerations, this kind of project could be realized only by a very large international collaboration and could be integrated in a larger programme like the cubic kilometer detector.

6. Conclusions

The different underground experiments have accumulated more than 15 kt·y of total sensitivity and no evidence of nucleon decay has been found in any decay channels studied.

In order to improve significantly the sensitivity to nucleon decay, progresses must be achieved in increasing the detector masses and in improving the background rejection.

It has been shown by the Kamiokande collaboration [8] that no significant background contamination can be expected below 100 kt·y for several decay channels. This means that the Super-Kamiokande experiment will yield a major improvement for decay channel like $p \to e^+\pi^0$. Moreover, the ICARUS project will allow a further improvement on the background rejection yielding to a considerable increase of the sensitivity to decay channels which still suffer frm a large background contamination.

To reach a sensitivity to lifetimes above 10^{34} years requires a detector with a mass greater than that of Super-Kamiokande by at least an order of magnitude which represents several 100 kton. The only way to realize such a huge detector is to go to a worldwide collaboration.

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