ICARUS EXPERIMENT *

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ABSTRACT

We briefly describe the current status of the ICARUS programme, including the 3 ton prototype R&D studies. The next step of the project will be the construction of a 600 ton module to be operated in the LNGS underground laboratory. A detailed description of the proton decay detection capability and of the lifetime limits achievable, both with the 5,000 ton final detector and with the 600 ton module are reported.

1.Introduction

As is well known, bubble chambers have played a fundamental role in Particle Physics. They provide unbiased events, in 3 dimensions, with the possibility of adding a magnetic field. Because of the high density of the liquid medium, bubble chambers can combine target and detector

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functions. Unambiguous discovery can be claimed at single (few) event level.

However, bubble chambers are not continuously sensitive, hard and costly to build and dangerous if operated underground.

An ideal detector for search of rare events in an underground laboratory, such as proton decay and neutrino interactions, would be a high resolution detector with an electronic read-out, a so called *electronic bubble chamber*.

With this aim, in 1985 the ICARUS programme was presented[1]. The final goal of the experiment is the construction of a multi-kton detector to study a variety of fundamental physics issues in the underground Gran Sasso laboratory[2]. After many years of intense R&D work, culminated in more than 4 years of continuous operating the 3 ton prototype at CERN[3], we are now ready to build and operate a 600 ton module in the Gran Sasso underground laboratory[4].

2.The 3 ton prototype

In 1989 the ICARUS collaboration decided to build a reasonable scale prototype[3] detector aiming to solve the main technological problems:

a) The liquid argon must be kept ultra pure even in the presence of a large number of feedthroughs for the signals and the high voltage, and with wire chambers, cables, etc. in the clean volume. The contamination of electronegative molecules must be kept to around 0.1 ppb to allow drifts on long distances (metres) without capture of the ionization electrons;

b) All the materials employed in the construction of the detector must be extremely clean and non-degassing and the feedthroughs between pure argon and the outside world must be completely tight to avoid contamination due to leaks;

c) The wire chambers must be able to perform non-destructive readout with several wire planes with a few mm pitch; they must be built out of non-contaminating materials and must stand the thermal stress of going from room to liquid argon temperatures; the precision and the reliability of the mechanics must be high and a good knowledge of the electric field in the detector must be granted;

d) In order to obtain a good signal-to-noise ratio, low-noise preamplifiers must be developed. It must be remembered that we work with no amplification in the liquid; the signal is very small, of the order of 10 000 electrons for a minimum-ionizing track in a 2 mm wire pitch;

e) Given the large amount of digitizations of the three-dimensional image, software architectures and algorithms must be developed for data reduction.

The cryostat, shown schematically in Figure 2.1, consists of two coaxial vertical stainless steel (AISI 304L) vessels. The shape of both the external

(1 in Figure) and the internal (2) vessels is a cylinder with hemispherical bottoms. The outer vessel has a diameter of 1.5 m, a height of 3.3 m and a wall thickness of 3 mm. The inner vessel has a diameter of 1.05 m, a height of 3.08 m and a wall thickness of 3 mm. The total internal volume is 2.61 m^3.

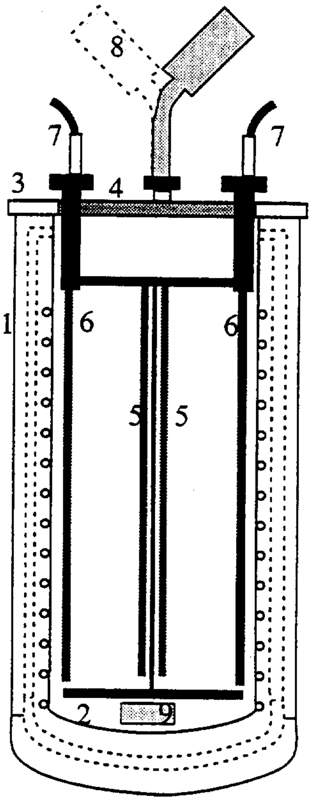

Fig. 2.1 : Schematic view of the mechanics of the detector. 1 is the outer vessel, 2 the inner vessel, 3 the annular flange, 4 the circular flange, 5 the wire chambers, 6 the cathodes, 7 the high-voltage feedthroughs, 8 the boxes containing the preamplifiers (two out of eight shown), 9 the purity monitor.

There are two wire chambers on each side of the central septum. Each chamber consists of three planes of wires. The first plane is a screening/focusing grid followed by the induction plane and finally by the collection plane. The induction plane is made by doublets of sense-wires (each doublet is read out by one amplifier) separated by 0.6 mm; the centres of two adjacent doublets are separated by 2 mm and there is a screen wire between them. The collection plane is made of sense-wires at a 2 mm pitch separated by screen wires.

The wires (stainless steel, 100 µm in diameter) are kept in position and under tension on the frame of the chamber by a structure made out of MACOR bars. They are held by small conical tubes crimped around them, while the tubes are held in turn by the holes drilled in the MACOR bar. Their diameter is 150 μm. In the case of the doublets of the induction plane we insert both wires in the same tube (300 μm in diameter).

3. The 600 ton module

It appears to us that the best way to reach the sensitive mass needed to fulfil our scientific goals is to go through an intermediate step between the 3 ton detector in operation at CERN and the major engineering design of the multikiloton detector[3]. A few hundred ton detector will insure that our extrapolation between 3 tons and a few thousand tons is done in the most efficient way.

This step-wise strategy will allow us to develop progressively, at the Gran Sasso Laboratory, (1) the infrastructure needed to build and operate our large detector, (2) the *in situ* experience needed in terms of safety but on a still modest liquid argon volume, and (3) to obtain a definitive and practical evaluation of our engineering choice for the final phase.

It quickly appeared to us, that a few hundred ton detector would at the same time allow an important first step in our scientific programme. While a sensitive mass in excess of a few thousand tons of liquid argon is clearly needed to achieve the 10^{34} years range in proton decay lifetime in a number of proton decay channels, many exotic channels have only been poorly investigated so far or not at all, and would be easily covered in this first phase. Atmospheric and solar neutrinos are areas which could be completely clarified in establishing whether the effects observed by Kamiokande and Homestakes are instrumental or genuine. Therefore we have chosen a detector size which is the largest which can be transported from an outside laboratory to the Gran Sasso Laboratory: two half detectors with a cross-section of 3.9 by 4.2 metres and a length of 19 metres, corresponding to a total internal volume of 465 m^3 and a sensitive mass of 540 tons of liquid argon. Moreover, we decided to use a 3 mm wire pitch instead of the 5 mm foreseen for the 5000 ton module, in order to allow for higher precision measurements. This is particularly beneficial for solar neutrinos, especially when this is combined also with the presence of a neutron absorber around the entire volume, in order to reduce the radioactivity background to a negligible level.

This intermediate step opens in addition the possibility to explore a new route towards larger detector volumes: the construction of a number of identical 600 ton detectors installed next to one another.

4. Proton decay detection

4.1 The multi kton detector

Thanks to its large sensitive mass (4.7 kton)[4] and to its spatial and energy resolution capabilities, ICARUS is an ideal device for nucleon decay detection, in particular for those channels that are not accessible to

Cherenkov detectors due to the complicated event topology, or because the emitted particles are below the Cherenkov threshold ($K^{\pm}$). Unlike the other large detectors for proton decay, ICARUS, with its excellent tracking and particle identification capabilities providing a much more powerful background rejection, can perform exclusive decay mode measurements. In particular, it is possible to distinguish between atmospheric neutrino events and true nucleon decays. Our Monte Carlo simulation has already verified this point for a number of decay channels.

We have performed a detailed event simulation based on the standard GEANT Monte Carlo code and the realistic events obtained contain very long tracks with redundant information, allowing particle identification and measurement of their energies with great precision.

Table 4.1 : Efficiency (ε), as defined in the text, for various nucleon decay modes

Decay mode	ε	**Decay mode**	ε
$p \rightarrow e^+ \pi^0$	0.42	$n \rightarrow e^+ \pi^-$	0.4
$p \rightarrow \nu \pi^+$	0.42	$n \rightarrow \mu^+ \pi^-$	0.37
$p \rightarrow \mu^+ \pi^0$	0.38	$n \rightarrow \nu \pi^0$	0.42
$p \rightarrow \nu K^+$	0.85	$n \rightarrow e^- K^+$	0.85
$p \rightarrow e^+ \pi^+ \pi^-$	0.13	$n \rightarrow e^+ \rho^-$	0.08
$p \rightarrow e^+ \rho^0$	0.08	$n \rightarrow e^+ \pi^- \pi^0$	0.13

Particle identification benefits greatly from the ability to measure the ionization loss (*dE/dx*). In particular, using *dE/dx* versus range only, an excellent separation is obtained between pions and kaons. As a consequence, many exclusive channels will be searched for simultaneously, both for proton and neutron decays for which discoveries can occur at the one-event level. This is certainly the main strength of the ICARUS technique.

In the absence of background, the limit on the nucleon lifetime reachable in T years of observation is given by the simple formulae:

$\tau_p > 1.2 \times M \times T \times \eta$ (10^{32} year) (90 % C.L.) for the proton (1a)

$\tau_n > 1.4 \times M \times T \times \eta$ (10^{32} year) (90 % C.L.) for the neutron (1b)

where M is the detector mass in kton and η is the overall detection efficiency.

In order to reduce neutrino-induced backgrounds we make use of the ability of ICARUS to fully reconstruct the events. Proton decay events are characterized by a definite value of the total energy and by the fact that the total momentum of the decay products must be zero. These features, which are true for a free nucleon, are also approximately verified for a nucleon bound in a nucleus, provided the decay products do not rescatter before escaping the nucleus. As a consequence, we also include in our definition of detection efficiency $\eta = \varepsilon_D \cdot \varepsilon$ the probability ε that the decay products do not interact with the nucleus in which they were produced, and the reconstruction efficiency ε_D.

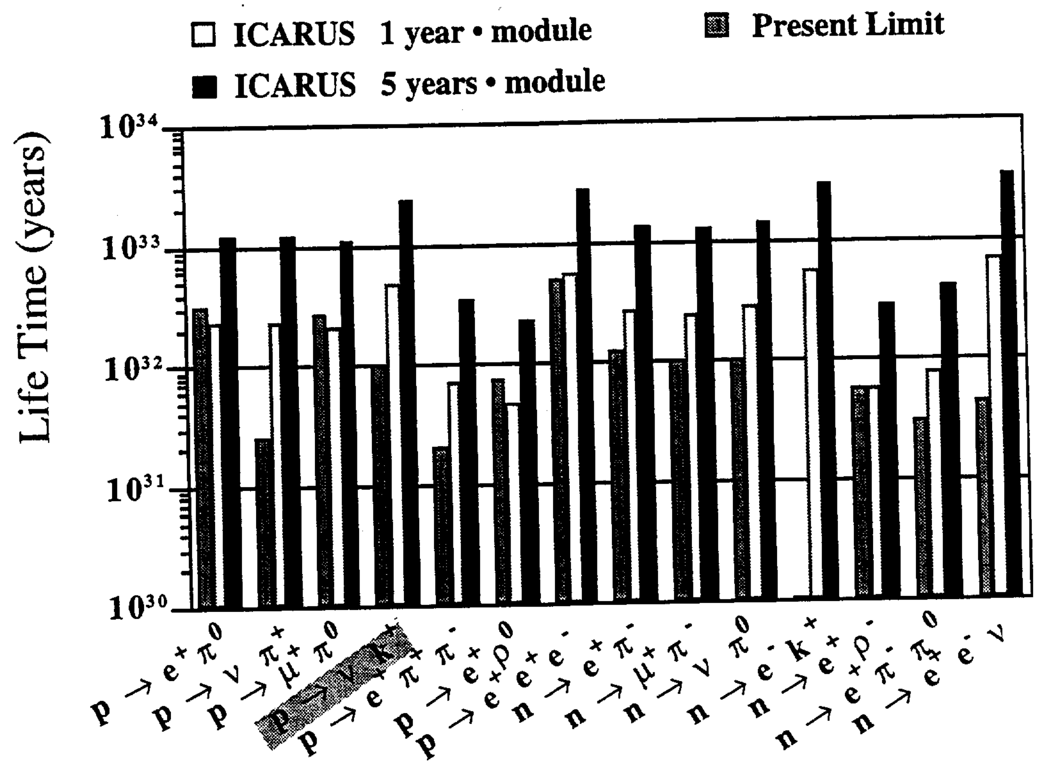

Fig. 4.1 : Comparison of present nucleon decay limits with the sensitivity of ICARUS for one and five years

These nuclear effects, the distortions of the energy and momentum distributions due to the nucleon Fermi motion, and the reinteraction of decay particles with the nucleus have been studied by Monte Carlo simulation methods.

Table 4.1 lists, for some of the main decay modes under consideration, the computed probabilities (ε) for the nucleon decay products to escape the argon nucleus without interacting.
For example, for the decay mode $p \rightarrow \nu + K^+$ we obtain $\varepsilon = 0.85$ and a corresponding lifetime limit $\tau_p > 4.7 \times 10^{32}$ (90% C.L.) years for one year of data-taking. In ten years of operation, ICARUS will be able to reach a proton lifetime of 5×10^{33} years for this most interesting decay mode. This would increase the present limit by about two orders of magnitude. For this decay mode in particular (as for many others) we don't expect to have any significant background.

Except for channels such as p → $e^+ \nu \nu$ for which the topology is identical to that of atmospheric ν_e charged-current events, the background corresponding to a data-taking period of one year is negligible. In order to obtain a preliminary estimate of the sensitivity of ICARUS, we have assumed that for all the other decay modes the background is indeed also negligible.

In summary, many nucleon decay modes can be searched for simultaneously and, after only one year of data taking, ICARUS will reach or exceed most present limits (Figure 4.1). The equivalent of five years of data will take us to the unexplored region between 10^{33} and 10^{34} years for some of the most relevant channels.

With the huge mass of liquid argon it is possible to conceive a measurement of the neutron-antineutron oscillations, taking into account the big reduction factor due to the nuclear potentials[6]. The efficiency to detect a neutron-antineutron oscillation (5 pions in average) in ICARUS is very high. The achievable limit for free n-n oscillation in one year running is of the order of 4.0×10^8 s, better than the present one[7].

4.2 The 600 ton module

Even with a relatively low mass, our test module can provide important contributions to the proton decay search, in particular for those decay modes (referred in the following as *exotic decay modes*) with high multiplicities (3 or 4 particles in the final state) or, more generally, with signatures particularly difficult to identify with previously used detector techniques.

One example of such decay modes is p → $e^+ \nu \nu$ which has been emphasised in our proposal[2] because it can be interpreted as the source of the excess electron-like events in the Kamiokande and IMB experiments. This type of event belongs to a class of decay modes with $\Delta B = -\Delta L$ which is one of the distinguishing features of $SU(4)^{\text{colour}}$ Grand Unification Theories. This model has been first proposed by J. Pati and A. Salam[5] in 1973.

With a sensitive mass of about 540 tons the ICARUS prototype can probe in one year, lifetimes up to 1.5×10^{32} years. Moreover, this module will have three readout planes and a better space resolution (3 mm^3 instead of 5 mm^3) with respect to the one foreseen for the big ICARUS, and therefore it will be even better suited for the analysis of complicated topologies. In this sense the physics programme of the 600 ton module will be, at least in part, complementary to the one of the full detector.

Table 4.2 reports the rates and the background expected for a 540 ton prototype in some of the channels characteristic of the Pati-Salam model, assuming that the nucleon lifetime is at the current experimental limit.

The ICARUS technique is particularly well suited to identify these decay modes, or any decay mode involving several charged particles in the final state. The detector techniques used so far, especially water Cherenkov detectors, do not allow to study these decay modes in an exclusive way, as can be seen from the relatively modest present limits. For most of them the background in ICARUS is expected to be negligible, hence one single event is sufficient for a discovery.

Table 4.2: For a number of exotic decay modes, the detection efficiency (including the fiducial volume cut), the present limits, the rates in the 600 ton module corresponding to the present limit are given.

Decay Mode	Efficiency	Present Limit (10^{31} years)	Events (year^{-1})
$p \to e^- \kappa^+ \pi^+$	0.36 (.9)	2.0	2.6
$p \to \mu^- \kappa^+ \pi^+$	0.36 (.9)	0.5	10.5
$p \to \bar{\nu} \pi^+$	0.36 (.85)	2.5	2.0
$p \to e^+ \nu \nu$	0.72 (.85)	1.1	9.6
$p \to \mu^+ \nu \nu$	0.68 (.8)	2.1	4.7
$n \to \mu^- e^+ \nu$	0.54 (.6)	4.7	2.1
$n \to e^- \kappa^+$	0.68 (.8)	3.2	3.8
$n \to \mu^- \kappa^+$	0.64 (.75)	5.7	2.0
$n \to e^- e^+ e^- \pi^+$	0.36 (.9)	0.1	12
$n \to e^- e^+ e^- \kappa^+$	0.81 (.9)	0.1	27
$n \to \mu^- e^+ e^- \pi^+$	0.36 (.9)	0.1	12
$n \to \mu^- e^+ e^- \kappa^+$	0.81 (.9)	0.1	27

Table 4.2 also reports the detection efficiencies for the various channels. These efficiencies include the requirement that the events are contained in the detector. For nucleon decay events, with the present geometry for the 600 ton module, it turns out that the containment request does not reduce very much the fiducial volume. Considering that a certain segmentation with relatively large dead zones (for supporting frames, internal electronic boards, etc.) will be probably present also in a single 5000 ton detector, the above consideration favours a strategy of using several 600 ton modules to reach the 5000 ton sensitive mass.

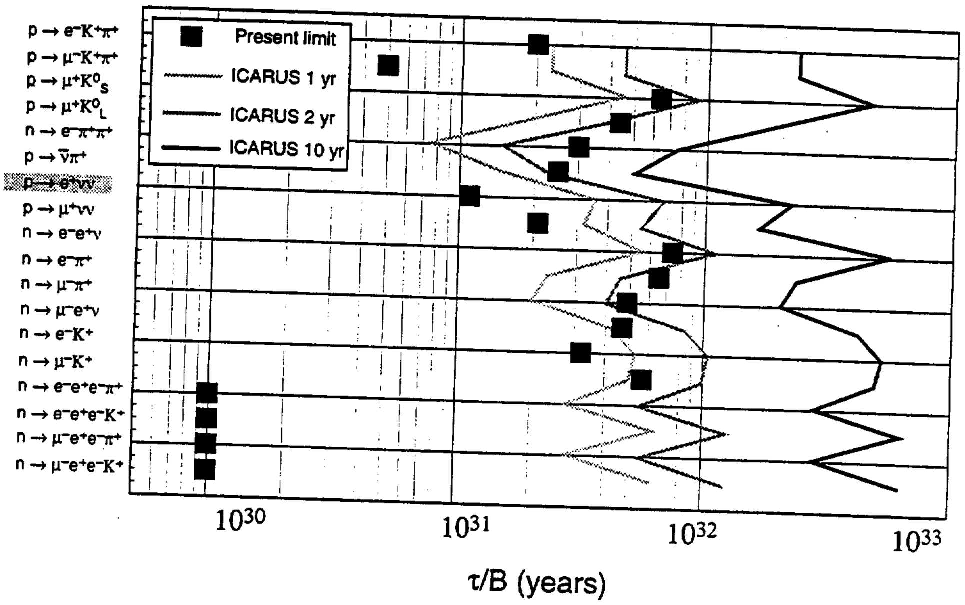

Fig. 4.2 : Present limits for a number of "exotic" proton and neutron decays together with the 90% ICARUS sensitivity, with the 600 ton module and for data taking periods of 1, 2 and 10 years.

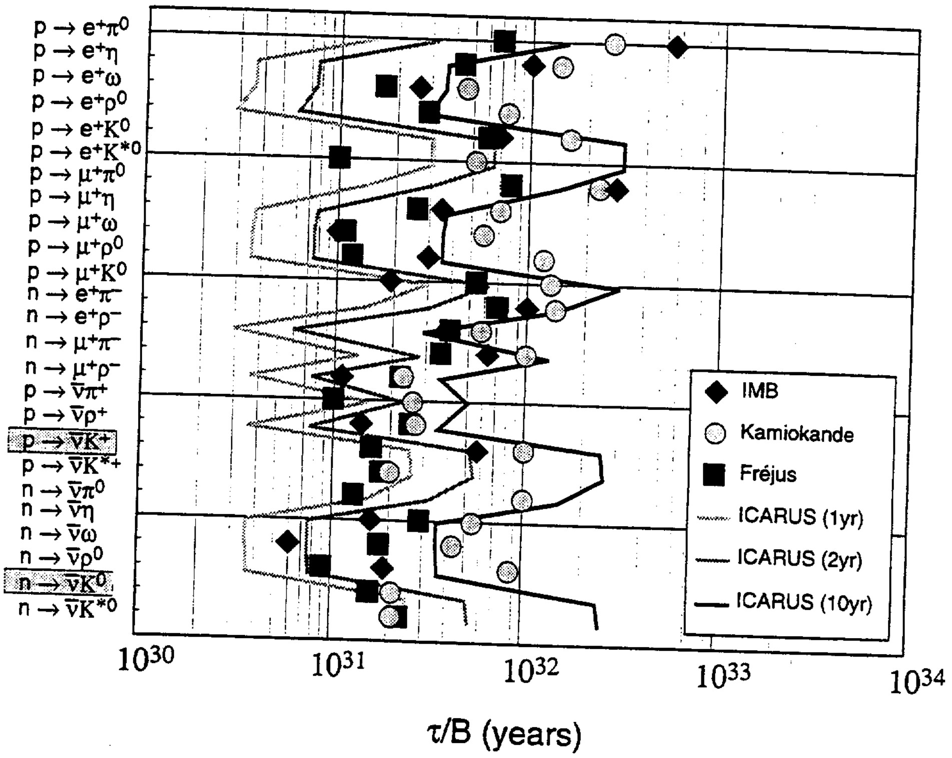

Fig. 4.3 : Present limits for a number of "standard" proton and neutron decays together with the 90% ICARUS sensitivity, with the 600 ton module and for data taking periods of 1, 2 and 10 years.

With our 600 ton module, in a few years, we will be able to explore a lifetime region exceeding 10^{32} years for most of the channels reported in the above tables, with a considerable improvement (a factor 5 to 100) of the present limits for the exotic channels (see Figure 4.2). It is clear that with one single module we cannot reach the lifetime limit of 10^{34} years (Figure 4.3) which is needed to fully test the minimal SUSY Gran Unification Theory and which is the final goal for the 5000 ton detector. We will nevertheless satisfy completely what is our requirement for this first phase of our programme and namely to extend the present knowledge of the nucleon stability over the widest possible range of decay modes at the same level of the presently best studied channels.

5. Conclusion

After many years of intense R&D studies, with more than 4 years of continuous operating the 3 ton prototype at CERN, the ICARUS experiment is now ready to start the construction of a 600 ton module to installed in the underground Gran Sasso Laboratory. As is reported in § 3, this step is intended to pursue two main goals:

- to establish all the important technical developments, such us the cryostat design, the read-out chamber technique, the electronics immersed in LAr, needed to scale up the detector size from 3 ton to several kton;
- to realize a complete physics programme, including atmospheric and solar neutrinos study, proton decay detection, at least in the exotic channels.

This step has already been approved and funded by Istituto Nazionale di Fisica Nucleare, for the Italian groups, and by DOE for the UCLA group.

The construction of the cryostat will start soon in Italy and the foreseen completion of the whole detector and the start of data taking at the LNGS is expected for the year 1999.

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