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ICARUS : IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

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ICARUS:
IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

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ABSTRACT

Since the initial ICARUS proposal [1], intense activity in research and development has firmly established the technology of using ultra-pure argon, and the readout technique of ionization data, for very large sensitive volumes, first proposed in 1977 [2]. A 3-t liquid-argon time projection chamber working as an electronic bubble chamber with the ability to provide 3-D imaging of any ionizing event, together with an excellent calorimetric response, has been operating successfully for more than one year at CERN. The device is continuously sensitive and self-triggering. The present phase of the ICARUS programme consists of the construction and operation of a much larger volume of liquid argon (15,000 t) in the Gran Sasso tunnel, in order to address several fundamental physics phenomena.

1. ICARUS: an Innovative Detector Technology

The principal asset of the ICARUS programme is the development of a new detector technology which allows the detection of low-energy (down to a few MeV) electrons produced by solar neutrino interactions and nucleon decay products, in a very large volume of liquid argon. ICARUS is a large liquid-argon detector (three modules of 5,000 t each) which provides bubble-chamber quality images for neutrino interactions or proton decays. Such a large scale detector programme had to be subdivided into a series of steps or phases in order to verify the soundness of the various technologies involved. The first phase of the experiment [3] consisted of an R&D programme which led to the construction of a 3-t prototype at CERN to ascertain the technical feasibility of the method proposed.

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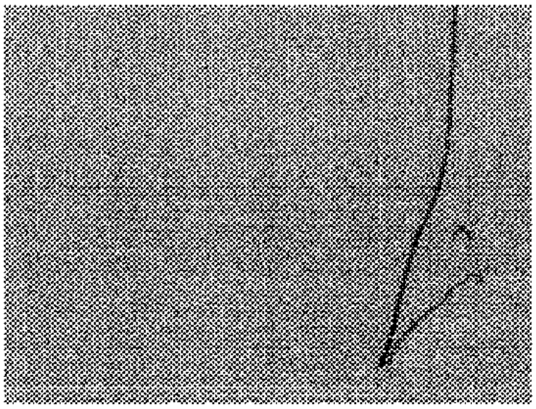
1.1 The 3-t Prototype

The successful and steady operation of a 3-t prototype since May 1991 at CERN is a major milestone in the ICARUS programme. The first events taken with cosmic rays immediately reminded us of Gargamelle-type bubble-chamber events, with a 'bubble' size of $2 \times 2 \times 2$ mm^3. The major breakthrough is that these events are self-triggering, the readout is entirely electronic, each bubble gives a measurement of the energy deposited by a particle, and the technique can be extended to practically unlimited active volumes.



Stopping Muon with delayed Electron

Hadronic Shower from Cosmic Ray

The main technological challenge was to adapt to a large scale volume the techniques which had previously been established on a smaller scale, namely argon purification (less than 0.1 ppb of electronegative impurities), extreme cleanliness of the material employed, high reliability of feedthroughs to avoid leaks, the construction of high-precision wire planes able to resist thermal stresses, and the development of very low noise preamplifiers to collect small ionization charges.

1.1.1 The detector

The detector consists of two independent semi-cylindrical sections, each facing a 2.4×0.9 m^2 wire chamber made of three parallel planes of wires: (a) a screening/focusing grid, (b) an induction plane (450 sense wires), and (c) a collection plane with its wires perpendicular to the induction wires (1200 sense wires). The sense wires' pitch is 2 mm, and the maximum electron drift distance is 42 cm. The signals collected by the sense wires are first carried, by low-capacitance (40pF/m) flat Kapton cables immersed in the liquid argon, to the 2100 feedthroughs which take them out of the argon container. The front end electronics (low noise amplifiers) is situated immediately on top of the feedthroughs, and can be maintained at a low temperature (–20 C) to reduce its noise.

1.1.2 Argon purification

The purification process is divided into two steps. Industrially clean argon (~ 1 ppm of oxygen equivalent impurities) is first evaporated and passed through a molecular sieve followed by an oxysorb, and then condensed into the detector. At this stage the purity reaches the 0.1 ppb level. Degassing of surfaces, and possible leaks, can degrade the argon purity, and therefore necessitates a continuous recirculation system which operates as follows. Owing to heat losses of the dewar, liquid argon evaporates naturally at a rate of 5 litres of liquid per hour. The vapour produced goes through a molecular sieve and an oxysorb filter, and is condensed back in a heat exchanger which lies above the dewar, so that the liquid argon produced can, by gravity, go back to the bottom of the detector volume. This purification procedure has been working extremely well, maintaining the electron lifetime continuously above 2.5 ms, over a period which now exceeds eighteen months.

1.1.3 Detector performance

The 3-t prototype is being studied carefully to understand its performance, and to determine the best techniques to be used in the 5,000 t modules for Gran Sasso. The main conclusions are all very good:

– Cleaning procedures for components, also used at LEP, will also be satisfactory on a large scale.

– There are hardly any limitations in the choice of materials which will be in contact with the liquid argon. In addition to standard stainless steel, Kapton, Teflon, and many types of ceramics can be used.

– The argon purification system is under control. A test in the liquid phase has shown that the speed of purification needed for large volumes of argon can be reached (800 litres/hour/purification line). Liquid phase purification is also desirable because of the energy-saving aspect.

– The mechanical design is sound. In particular, the present wire failure rate which extrapolates to 5/10,000 is now understood (crimping technique).

– The electronics is performing well, without surprises (900 electrons equivalent noise charge). It is clear that the lowest noise configuration must be chosen whenever possible, since noise is the limiting factor for space and energy resolution.

Many parameters of the detector performance have been measured using both cosmic rays and 6.13 MeV photons from a ^{238}Pu–^{13}C radioactive source, and confirm that the ICARUS technique is well understood.

The spatial resolution in the drift direction was measured: 150 μm for a signal-over-noise ratio of 10, almost independent of the electric field and drift distance. In a dedicated test with 5 GeV pions at the CERN PS, using a 24 cm chamber with the same wire spacing as the 3-t prototype, a 58 μm resolution was obtained [4] with a signal-over-noise ratio of 20.

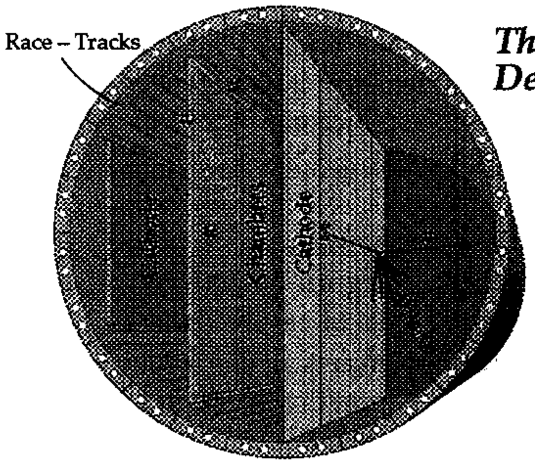
A detailed report of measurements made with the 3-t prototype can be found in Ref. [5].

The conclusion is that the situation is extremely good, the 3-t prototype is performing very well, and we have learned a great deal from it. It is now possible to finalize the design, and to build the full scale detector to be installed in the Gran Sasso tunnel.

1.2 The Gran Sasso Project

1.2.1 The mechanics

ICARUS consists of three cryostat modules of cylindrical shape, with flat ends, making optimal use of the experimental Hall C in the Gran Sasso Underground Laboratory, about 100 km from Rome, Italy. The laboratory is 963 m above sea level protected by about 3,100 m of water equivalent rock under Mount Aquila in the Gran Sasso mountains.



The ICARUS Detector

The design criteria have been driven by three main concerns: performance, reliability, and safety. The design was chosen in order to fit the largest possible volume of liquid argon in the available cavern, and to minimize the risk of liquid argon spill and liquid argon contamination. It is a modular construction of identical and independent vessels, characterized by a 'double hull' structure very familiar in the oil and gas tanker industry, with the following main features:

– an inner vessel containing about 4700 m^3 of sensitive liquid argon protected by an evacuated double wall.

– an outer vessel (about 18 m diameter and 25 m long) to provide thermal insulation (evacuated superinsulation), and a further protection against argon spill. The outer vessel is made of Fe–Ni (9%) alloy, a standard construction material for liquid CH_4 containers. If this alloy fulfils the stringent surface cleanliness requirements of ICARUS, it will also be used for the inner vessel, which otherwise will be made of 304L stainless steel.

– all openings for instrumentation, feedthroughs, main holes, etc. are located on the top of the cryostat.

– the ionization information is read by two double wire chambers situated 3.9 m away from both sides of a central high voltage plane. High voltage race tracks running parallel to the module axis provide the desired uniform electric field configuration.

1.2.2 The electronics and readout

The 50,000 channel ICARUS Imaging Readout is similar to the one developed for the 3-t prototype, but with a wider dynamic range because of the broad spectrum of phenomena to be observed, and with the addition of a hit finder processor (ASIC) per group of 8 wires, allowing real time pulse identification. This system provides continuous readout of the whole detector without dead time, and is based on commercially available standard components used in television applications (SAMUX, FADC, VDRAM).

The hit processor is a fall-out of the current research and development at CERN, in preparation for the next generation of experiments for the LHC.

2. The ICARUS Physics Programme

2.1 ICARUS and the European High-Energy Physics Strategy

The present European high-energy physics accelerator programme for the 1990's, and the beginning of the next millennium, mainly based on LEP, HERA, LEP-200, and the LHC needs to be complemented by a non-accelerator approach in areas inaccessible by accelerator techniques, for instance:

(i) Grand Unification schemes can be directly tested both in the neutrino sector (see-saw mechanisms), and in proton-decay experiments. Monopoles in this respect are equally relevant, but they have probably been diluted too much by inflation to be easily observable.

(ii) The understanding of fermion families requires the detailed knowledge of all the members of the family, in particular neutrinos, and only long base-line neutrino oscillations (vacuum and matter) experiments may provide the sensitivity to the very small masses which seem to be relevant.

There is therefore a natural complementarity between accelerator and non-accelerator high-energy physics approaches to the fundamental issues facing us today, and it is in this spirit that the ICARUS experiment was conceived.

2.2 The Physics Goals of ICARUS

The ICARUS Collaboration intends to make full use of the powerful detector technology developed, to provide definite answers to some of the most burning scientific issues, described below.

2.2.1 Search for nucleon decay up to lifetimes approaching 10^{34} years

Precision measurements of coupling constants at LEP have shown that the unification of forces does not occur naturally in the Standard Model (curves miss by 9 standard deviations). However, in the framework of the Minimal Supersymmetric Model, unification is possible, and the unification scale is of the order of 10^{16} GeV. The proton-decay issue is therefore still entirely open.

With ICARUS and a sensitive mass of 4,700 t per module, many exclusive channels can be searched for simultaneously. In addition, the possibility of using a CERN neutrino beam aimed at Gran Sasso provides a unique tool to calibrate the background. Within one year ICARUS will either reach or exceed all world limits, and depending on the number of modules built, will probe part or most of the lifetime region between 10^{33} and 10^{34} years in more than 10 different decay channels. The simulation of proton and neutron decays, clearly show that with the good energy resolution and particle identification of ICARUS, nucleon decays will be observed with an exceedingly small residual background from neutrino interactions.

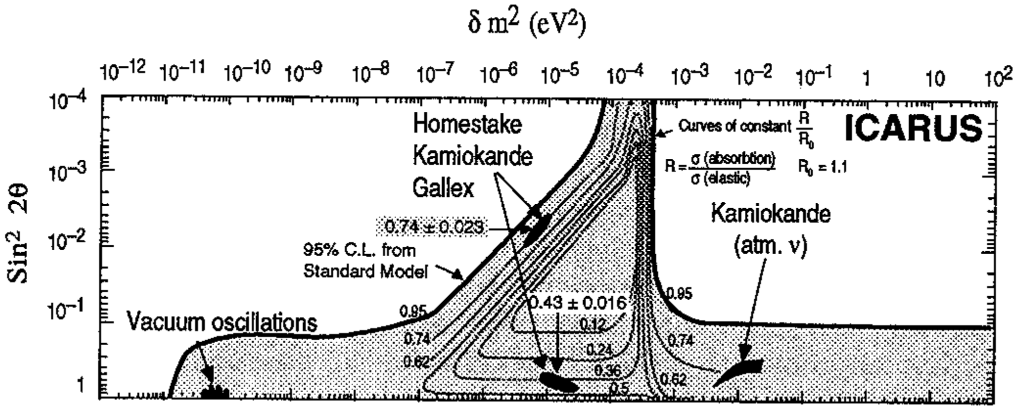
2.2.2 High statistics, Solar Model-Independent study of Solar neutrinos

The systematic investigations of neutrino properties are carried out in three different channels: solar neutrinos, neutrinos from a CERN accelerator beam, and cosmic ray neutrinos.

The definitive study of the solar neutrino puzzle requires the simultaneous observation of $\nu_{e,\mu,\tau} + e \rightarrow \nu_{e,\mu,\tau} + e$, and of inverse β-decays, in real time and with ample statistics. This is precisely what ICARUS is designed to do.

The reactions used for the direct observation of solar neutrinos from the ^{8}B cycle are : (1) $\nu_x + e \rightarrow \nu_x + e$, for which 2900 events/year/module are predicted in the electron elastic channel assuming the Standard Solar Model rate, and an efficiency of 69 % for $E_e > 5$ MeV; (2) $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e$, a super-allowed transition [6] followed by (${}^{40}K^* \rightarrow {}^{40}K + 1$ or $2\,\gamma$ [2 MeV]), for which the Standard Solar Model predicts about 2400 events/year/module, including 70% detection efficiency assumed in ICARUS for $E_e > 5$ MeV.

The distinctive properties of the recoil electron energy spectrum, together with the detection of photon energy associated with the ${}^{40}K^*$ decay, allows the ratio R of elastic electron scattering to absorption cross-sections to be measured.



With one year of data ICARUS can separate the present two Mikheyev–Smirnov–Wolfenstein (MSW) solutions by 10 standard deviations (statistical). The sensitivity region shown indicates that after one year ICARUS detects a 5% departure from the central value of the Standard Solar Model prediction.

2.2.3 Long base-line neutrino oscillation study using CERN as a ν_μ source

There is increasing evidence (atmospheric neutrino studies) that a specific region at small Δm^2 (10^{-1} to 10^{-5} eV^2) should be carefully studied. This requires neutrino oscillation experiments to extend the base-line outside the limits of the laboratory. A feasibility study [7] has shown that it is possible to send a CERN ν_μ beam to Superkamiokande (matter effects possible) or to Gran Sasso.

Artificially-generated neutrinos (neutrino beams) offer several clear advantages:

– The energy spectrum is more sharply peaked and better known than for atmospheric neutrinos.

– The energy can be tuned.

– One can switch between neutrinos and anti-neutrinos (interesting for matter effects).

– Known direction and timing allow efficient background rejection.

– Known initial beam composition (almost entirely ν_μ or $\bar{\nu}_\mu$).

– High rate for statistical accuracy.

2.2.3.1 $\nu_\mu \leftrightarrow \nu_e$ oscillations

The optimal conditions are obtained with 80 GeV protons from the CERN SPS (3.0×10^{13} protons on target every 2.4 s). The 400 GeV proton beam gives a similar sensitivity in $\sin^2(2\theta)$ (2.0×10^{-3} vs 1.5×10^{-3}), but a somewhat worse Δm^2 sensitivity (7.5×10^{-4} vs 1.5×10^{-4} eV^2).

There are two types of background to charged-current interactions from genuine ν_e coming from a ν_μ oscillation:

(i) ν_e in the initial beam: they mostly come from K decays. Because their transverse momentum is larger than ν_μ coming from π decays, as the distance increases their proportion decreases, and at Gran Sasso they are practically negligible for 80 GeV protons (2.5×10^{-4}).

(ii) Neutral current interactions of ν_μ producing a recoiling jet with π^0's faking electrons (1.5 π^0/Jet). In ICARUS, π^0's can be identified from their decay properties (separation of the photon showers), from the shape of the shower, and from ionization information. A detailed Monte Carlo simulation has shown that the π^0 background can also be made practically negligible in the 80 GeV proton case (≤ 0.1 %).

2.2.3.2 $\nu_\mu \leftrightarrow \nu_\tau$ *oscillations*

The sensitivities are comparable for proton energies of 80 and 450 GeV. At least three different methods can be used.

(a) Disappearance method: by measuring the number of muons produced in the rocks near ICARUS and coming from the direction of the CERN beam. This number of muons is proportional to the number of ν_μ's in the beam. It is then compared with the total number of neutrino interactions (CC + NC) in the detector, which is proportional to all neutrino flavours.

(b) Appearance method: by comparing the number of ν_μ CC interactions in the detector with the number of NC interactions which is proportional to the combined ν_μ and ν_τ number.

(c) Direct appearance measurement: by searching for ν_τ charged-current events producing a tau lepton. Several channels may be used, for instance $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$.

The resulting ICARUS sensitivity for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations extends at least to $\sin^2(2\theta) = 5.0 \times 10^{-2}$, and $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2.

2.2.3.3 *High statistics study of atmospheric neutrinos*

Kamiokande has shown that atmospheric neutrinos can be used to study oscillations [8]. A possible method consists in recognizing a variation in the neutrino flavour composition between upgoing and downgoing neutrino interactions. The full event reconstruction capability of ICARUS allows a precise and unambiguous measurement of upward- versus downward-going neutrinos, with large statistics. In particular, the excellent e/μ separation in ICARUS, and precise energy measurement, allow an accurate reconstruction of the neutrino energy spectrum, and flavour composition. Normalizing to the atmospheric neutrino flux, and composition from downward-moving neutrino interactions, one exploits effectively the long base-line range (up to 12,000 km) provided by the earth, to study $\nu_e \leftrightarrow \nu_\mu$, $\nu_e \leftrightarrow \nu_\tau$, and $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

ICARUS can detect neutrino interactions down to a few MeV. The total number of charged-current events expected for atmospheric neutrinos, in 2π steradians, assuming no oscillations, is of the order of 600 per year per module based on flux [9]. The flavour composition of downgoing neutrinos is expected to be approximately 35% ν_e, and 65 % ν_μ.

The high statistics will allow studies of base-line variations from angular distributions. The expected Δm^2 sensitivity should at least extend down to 10^{-4} eV^2.

2.2.3 Astrophysical and cosmological studies:

There are several classes of astrophysical and cosmological phenomena which can be studied with a neutrino telescope such as ICARUS.

(i) In addition to the study of intrinsic neutrino properties, solar neutrinos constitute a window for the understanding of the neutrino production mechanism inside stars. The electron recoil energy distribution for elastic scattering and absorption events, and their fluxes, will provide direct information on ^8B solar neutrinos.

(ii) The search for neutrino bursts from Supernova Collapses (Galactic, extra-galactic), and for Relic Supernova Neutrinos, will provide important new constraints on standard models. The search for new sources of low-energy neutrinos or antineutrinos uses the reaction $\nu_X\ e \rightarrow \nu_X\ e$, where x stands for any type of neutrino or antineutrino. A practical threshold is $E_e \geq 5$ MeV, which can be compared with the energy of supernova neutrinos above 10 MeV. There is a unique energy window above the solar ^8B neutrinos and below cosmic neutrinos where one could detect neutrinos coming from all the supernovae which have occurred in the history of the Universe. These neutrinos are expected to be red shifted but not thermalized.

More generally, it is expected that the observation of cosmic neutrinos will greatly complement the observation of high-energy γ rays. Neutrinos can be tracers of the production mechanism. We expect high-energy cosmic neutrinos to be produced by hadron decays, mainly charged pions, while γ rays may come either from electron (Bremsstrahlung, synchrotron, Compton, and pair emission in the interstellar medium), or from hadronic origin (π^0 decays). Since neutrinos have no electric charge, they can also be a tracer of the source. ICARUS, with its excellent energy and direction resolution, combined with its unique particle identification capability, will bring, in many instances, the information needed to complement present and future γ ray observations.

ICARUS should open a new window in our understanding of the Universe and of its 'Big Bang' origin.

3. Conclusion

With the successful operation of the 3-t prototype constructed at CERN, ICARUS is well under way. We are convinced that the new technology pioneered by ICARUS will provide a new insight into many fundamental aspects of physics, ranging from particle physics to astrophysics, and cosmology.

ICARUS has entered the final phase of the project, and its schedule is well adapted to the availability of the CERN neutrino beam, which is an important aspect of the programme for direct neutrino studies, and for proton decay background calibration. A possible scenario is that the CERN neutrino beam, which will take about two years for construction, and one year for commissioning, can be ready by 1997. The ICARUS Collaboration is planning to test a full wire plane chamber in a 15 m-long argon container in 1994, while completing a first large module prototype and finalizing the design. The construction of the first ICARUS module would span the period 1994 to 1997, and we expect the first data taking to start in 1998.

Acknowledgments

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