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PHYSICS WITH THE ICARUS DETECTOR* **

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The multipurpose ICARUS detector, with its large sensitive volume, high granularity, excellent tracking and particle identification capabilities, is an ideal device for searching for phenomena beyond the Standard Model. A vast physics program, including accelerator (CNGS neutrino beam), and non-accelerator (supernova, atmospheric, and nucleon decay) physics, planned for the ICARUS detector, is reviewed.

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1. Introduction

Series of successful technical tests of the first ICARUS 600 tons module (T600) in Pavia/Italy in 2001 has proven that the liquid argon time projection chamber technology reached maturity. The analysis of collected cosmic rays data shows excellent capabilities of the detector. Now the T600 is ready for the installation in the underground Gran Sasso Laboratory/Italy. The final total mass of the ICARUS detector will be of the order of 3000 tons. The bubble-chamber quality of the ICARUS data will provide additional (to the currently operating large volume underground detectors) contributions in the field of rare events, like neutrino interactions or nucleon decay. The ICARUS physics potential for the final mass of liquid argon has been

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described in [1]. The results possible to achieve with the first T600 module have been reported in [2]. In this paper a brief description of ICARUS physics program is presented.

2. The ICARUS detector

The ICARUS detector is a liquid argon (LAr) time projection chamber working as an electronic bubble chamber. Charged particles penetrating the detector volume produce, in highly purified LAr, ionizing electrons which drift to the anode wires, under the action of an electric field. Non-destructive readout of electron signals from three parallel planes of anode wires (planes 3 mm apart, with 3 mm wire pitch, oriented at $0°$, $\pm 60°$ angles), together with the electron drift time, allow for three-dimensional reconstruction of particle tracks. Thanks to the complete isotropy of the detection technique, the ICARUS apparatus will allow collecting, in the same data taking process, both the beam and the cosmic ray associated events. This detection technique has been proposed in 1977 by Rubbia [3]. Intense ICARUS Collaboration R&D work and production of several prototypes, bigger and bigger in LAr volume, demonstrated the feasibility of this technique. The last prototype was the "industrial" T600 module filled with 600 tons of LAr. It has successfully been tested (on the Earth surface) in Pavia/Italy in 2001. During over 100 days of continuous data taking over 29,000 cosmic rays events have been collected. Additional modules, up to the total mass of 3000 tons of LAr, are foreseen to complete the final detector configuration to be mounted in the LNGS (Gran Sasso/Italy) Hall B. The most important ICARUS detector parameters and features are the following (for details see Ref. [4]):

- 3D reconstruction of any ionizing event with a spatial resolution of 1 mm in directions perpendicular to the drift coordinate, and 0.15 mm along the drift coordinate,
- muon momentum resolution (from multiple scattering): $\pm 20\%$ at 10 GeV/c,
- energy deposition, range, angles and multiplicities measurements,
- particles identification by means of dE/dx *versus* range measurement,
- continuous sensitivity and self-triggering.

3. CNGS neutrinos

The new CERN–Gran Sasso (CNGS) ν_μ beam [5] will have wide energy distribution with a mean value of 17 GeV. After traveling the distance of about 732 km in the Earth, neutrinos reach experimental halls in the Gran Sasso Laboratory. Very small contamination of ν_e (10^{-2}) and ν_τ (10^{-7}) in the CERN–Gran Sasso (CNGS) muon neutrino beam will allow for the neutrino oscillations studies in the neutrino appearance experiment, by measurements of ν_e and ν_τ CC interactions. In this paper we discuss only the appearance of ν_τ, and concentrate on the $\tau \to e\nu\nu$ decay channel which gives the main contribution to the expected number of events (see Table I). For this channel, the main sources of background are: electrons from the CC interactions of the ν_e and $\bar{\nu}_e$ components of the CNGS beam, electrons from Dalitz decays, misidentified charged and neutral pions ($e\pi^\pm$ and $e\pi^0$ discrimination), and ν_μ CC events when the leading muon escapes detection. The search for the ν_τ signal is based on the kinematical suppression of the background by applying the following criteria: an unbalanced total momentum in the plane transverse to the incident neutrino direction (due to neutrinos from the τ decay), and a kinematical isolation of hadronic prongs. The analysis is based on the likelihood in three dimensions: E_{visible}, $P_{\text{TOT}}^{\text{missing}}$, and $P_{\text{TOT}}^{\text{lepton}}/(P_{\text{TOT}}^{\text{lepton}} + P_{\text{TOT}}^{\text{hadron}} + P_{\text{TOT}}^{\text{missing}})$. The discrimination is obtained from the ratio of the signal likelihood to the background likelihood. Table I summarizes the results of the ν_τ appearance searches in the "golden" electron channel, and two τ hadronic decay channels: deep-inelastic (DIS) with energetic hadronic jet and large final state multiplicity, and quasi-elastic (QE) with soft hadronic jet and small final state multiplicity. For $\Delta m_{23}^2 = 3.0 \times 10^{-3}$ eV^2 17 events are expected (with background smaller that one event). This rate is practically the same as the one expected in the OPERA experiment [7].

TABLE I

Expected number of τ and background events for 3 kton $\times$ 5 years, and $5 \times 4.5 \times 10^{19}$ pots [6]. Signal events correspond to full mixing and two values of Δm_{23}^2.

Decay mode	Signal $2.5 \times 10^{-3}\,\text{eV}^2$	Signal $3.0 \times 10^{-3}\,\text{eV}^2$	Background
$\tau \to e$	9.0	13.0	0.7
$\tau \to \rho$ DIS	1.5	2.2	<0.1
$\tau \to \rho$ QE	1.4	2.0	<0.1
Total	**11.9**	**17.2**	**0.7**

4. Atmospheric neutrinos

The expected number of atmospheric neutrino events (see Table II) will be modest in comparison with, for example, SuperKamiokande statistics. However, the measurement of all processes, electron, muon and tau neutrino CC events, and all NC events, without detector biases and down to the kinematical threshold, and using a different experimental technique, will give new information about atmospheric neutrinos. Muon-like (electron-like) events contain an identified muon (electron) and correspond to $\nu_\mu/\bar{\nu}_\mu$ ($\nu_e/\bar{\nu}_e$) CC processes. Samples of muon- and electron-like events are divided into "fully contained" (all registered particles are visible completely within the detector volume), and "partially-contained" events (with lepton escaping the detector volume). The precise reconstruction of final state topologies ("no proton" — with no identified proton with kinetic energy above 50 MeV, "one proton" — with identification of a single recoil proton, and "multi-prong") will allow for a precise determination of the incoming neutrino direction and energy. Furthermore, the SuperKamiokande [8] $P_{\rm lepton}$ threshold of 400 MeV/c (momentum of the leading lepton) was used to split the samples of muon- and electron-like events, and one can see that almost 50% of the events are below it. Therefore, the ICARUS experiment can really improve our understanding of the low energy atmospheric neutrinos. Also, a significant number of NC events will be observed. Thanks to the excellent e/π^0 separation, this sample will be practically free of background.

5. Supernova neutrinos

Supernova neutrinos can be detected in the ICARUS detector by observing electron neutrino/antineutrino absorption on argon

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^- \,,$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+ \,,$$

and neutrino/antineutrino elastic scattering on electrons (sensitive to all neutrino spices)

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- ,$$
$$\bar{\nu}_{e,\mu,\tau} + e^- \rightarrow \bar{\nu}_{e,\mu,\tau} + e^- .$$

Fig. 1 shows the expected number of supernova neutrino interactions ($N_{\rm SN}$) in the 600 tons of LAr (T600), integrated over the whole supernova neutrino energy spectrum, as a function of the distance neutrinos traveled in the Earth. In order to obtain these results we have applied the following assumptions: supernova explosion at the distance of 10 kpc from the Earth

TABLE II

Expected number of atmospheric neutrino events in case of no oscillations occur and assuming $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing ($\sin^2 2\theta = 1.0$) for two values of Δm^2_{23} (given in eV^2), and for 2 kton $\times$ year. Only statistical errors are quoted [2].

	No oscill.	Δm^2_{23}=1.0×10^{-3}	Δm^2_{23}=3.5×10^{-3}
Muon-like	270±16	198±14	188±14
Fully-contained	134±12	96±10	88±10
Partially-Contained	136±12	102±10	100±10
No proton	104±10	74±9	68±8
One proton	82±9	60±8	58±8
Multi-prong	84±9	64±8	62±8
$P_{\rm lepton} < 400$ MeV/c	114±11	80±9	74±9
$P_{\rm lepton} \geq 400$ MeV/c	156±12	118±11	114±11
Electron-like	152±12	152±12	152±12
Fully-contained	100±10	100±10	100±10
Partially-Contained	52±7	52±7	52±7
No proton	64±8	64±8	64±8
One proton	48±7	48±7	48±7
Multi-prong	40±6	40±6	40±6
$P_{\rm lepton} < 400$ MeV/c	74±9	74±9	74±9
$P_{\rm lepton} \geq 400$ MeV/c	78±9	78±9	78±9
NC-like	192±14	192±14	192±14
TOTAL	614±25		

with 3×10^{53} ergs energy released as neutrinos; standard thermal Fermi–Dirac neutrino production spectra with $T_{\nu_e} = 3.5$ MeV, $T_{\bar{\nu}_e} = 5.0$ MeV, $T_{\nu_\mu,\nu_\tau,\bar{\nu}_\mu,\bar{\nu}_\tau} = 8.0$ MeV (all chemical potentials set to zero); three flavors neutrino oscillations in supernova considered according to [9]; current LMA-I (Large Mixing Angle) solution parameters $\Delta m^2_{21} = 7.1 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{12}) = 0.84$, $\sin^2(2\theta_{23}) = 1.0$, two values of $\sin^2\theta_{13}$, the first one equal to 0.02 (Large θ_{13}) and the second one equal to 1.0×10^{-7} (Small θ_{13}), Dirac's phase δ equal to zero; realistic PREM-I [10] Earth matter density profile for neutrino mass states regeneration in the Earth. Calculations have been performed for both, Direct (normal) and Inverted, mass hierarchies in the neutrino energy range 0.1–100 MeV [11]. We can see that the dominant contribution to the total number of interactions comes from the ν_e absorption on Ar. The distance traveled by neutrinos in the Earth has only little influence on $N_{\rm NS}$ for any combination of θ_{13} and mass hierarchy. In case of small θ_{13} the value of $N_{\rm NS}$ does not depend on the mass hierarchy scheme at all.

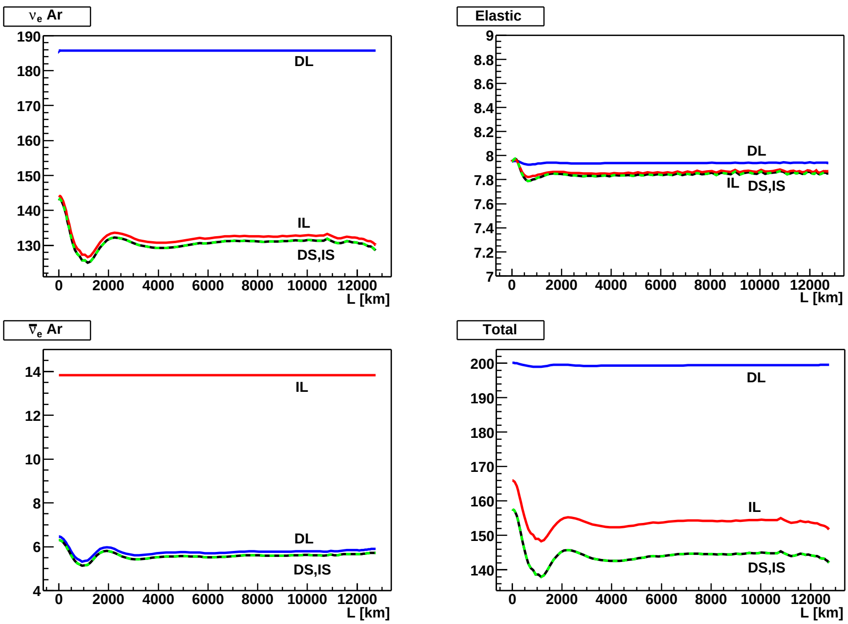

Fig. 1. The expected number of supernova neutrino interactions in the T600 module of the ICARUS detector (integrated over the whole supernova neutrino energy spectrum) as a function of the distance, L, neutrinos traveled in the Earth, for different combinations of mass hierarchy and θ_{13} (DL — Direct mass hierarchy and Large θ_{13}, IL — Inverted mass hierarchy and Large θ_{13}, DS — Direct mass hierarchy and Small θ_{13}, IS — Inverted mass hierarchy and Small θ_{13}).

6. Search for nucleon decay

The question of baryonic matter stability is of fundamental importance. Recently, the SuperKamiokande collaboration has studied some channels of possible proton decays [12, 13]. Their studies will be certainly continued giving new values of decay limits. However, in order to show the proton decay signal in water Cerenkov detectors one has to subtract the background statistically, whereas in the ICARUS detector, thanks to its excellent imaging and energy resolution, the nucleon decay can be discovered at the level of a single event. Moreover, nucleon decay channels with complicated event topology are also accessible for the LAr based detector. The minimum exposure needed to reach the present Particle Data Group [14] limits on several nucleon decay modes is presented in Table III, together with the estimation of backgrounds, due to atmospheric neutrino interactions. One can notice that there are channels which are practically free of background, and four years of running of the ICARUS detector in its final configuration (3 ktons of LAr) are sufficient to improve the current nucleon decay limits.

TABLE III

Needed exposure of the ICARUS detector to reach current PDG proton and neutron decay limits. Estimated number of background events for each decay mode at 1 kton× year exposure is also given [2].

Decay channel	Partial mean life (PDG'02 limit) (10^{32} years)	Exposure needed to reach PDG'02 limit (ktons × year)	Background events (1 kton×year)
$p \to \pi^+\bar{\nu}$	0.25	0.6	0.6
$p \to \mu^-\pi^+K^+$	2.45	2.2	< 0.1
$p \to e^+\pi^+\pi^-$	0.82	3.2	< 0.1
$p \to K^+\bar{\nu}$	6.70	6.0	< 0.1
$p \to \mu^+\pi^0$	4.73	9.9	< 0.1
$n \to e^-K^+$	0.32	0.3	<0.1
$n \to \mu^-\pi^+$	1.00	1.5	< 0.1
$n \to e^+\pi^-$	1.58	2.3	< 0.1
$n \to \pi^0\bar{\nu}$	1.12	2.4	0.5

7. Conclusions

The primary physics program that will be accomplished with the ICARUS detector at the underground Gran Sasso Laboratory/Italy has been described. Many interesting results concerning different aspects of neutrino physics will be possible to obtain thanks to the excellent quality of collected data, proved during about 100 consecutive days of T600 module tests. The T600 is the first step in reaching the total sensitive detector mass of 3000 tons, needed to complete the physics program. However, some results are already achievable with exposures of 1 or 2 kton × year. Apart from the primary physics program, the ICARUS detector will also allow for the measurement of the underground muon flux. Study of multiple muon events can bring information about composition of primary cosmic rays.

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