LANNDD - A Massive Liquid Argon Detector for Proton Decay, Supernova and Solar Neutrino Studies and a Neutrino Factory Detector

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Abstract

We describe a possible Liquid Argon Neutrino and Nucleon Decay Detector (LANNDD) that consists of a 70 kT magnetized liquid Argon tracking detector. The detector is being designed for the Carlsbad Underground Laboratory. The major scientific goals are:

1) Search for $p \to K^+ + \overline{\nu}_\mu$ to 10^{35} years lifetime
2) Detection of large numbers of solar neutrino events and supernova events
3) Study of atmospheric neutrinos
4) Use as Far detector for Neutrino Factories in the USA, Japan or Europe.

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1 Introduction

One option for next generation nucleon decay search instrument is a fine-grained detector, which can resolve kaons as well as background from cosmic ray neutrinos that are below the threshold for water Cerenkov detectors such as Super-Kamiokande (SK). One option for a next generation nucleon decay search instrument is a fine-grained detector, which can resolve kaons as well as background from cosmic ray neutrinos that are below the threshold for water Cerenkov detectors such as Super-Kamiokande (SK). Such a detector can make progress beyond the $few \times 10^{33}$ yr limits from SK for SUSY favored modes because the reach improves linearly with the time and not as the square root of exposure as in SK. It will be possible to discover nucleon decay up to about $\sim 10^{35}$ yr lifetime/branching ratio with an instrument of ~70 kT mass in liquid argon after a few years of exposure.

A second major goal for such an instrument, as demonstrated in a spectacular example of synergy in the last two generations of underground detectors, is the study of neutrino interactions and oscillations. Such a detector can make neutrino oscillation studies using the cosmic ray neutrinos alone (being able to resolve muon neutrino regeneration, detect tau's and tighten measurements of Δm^2 search for other mixing than $\nu_\mu \to \nu_\tau$). But coupled with a neutrino factory, this detector, outfitted with a large magnet, offers the advantage of being able to discriminate the sign not only of muon events, but of electron events as well. Given the bubble-chamber-like ability to resolve reaction product trajectories, including energy/momentum measurement and excellent particle identification up to a few GeV, this instrument will permit the study of the neutrino MNS matrix in a manner which is without peer.

One may question whether such a marvelous instrument is affordable, by which we mean buildable at a cost comparable or less than the neutrino source cost. It is indicated by simple scaling from existing experience with ICARUS, that such an instrument will cost out in the class of a large collider detector instrument and represents a straightforward extrapolation of existing technology.

As expected for such a large, isotropically sensitive, general-purpose detector, there are *many* ancillary physics goals that can be pursued. This device would allow exploration of subjects ranging from the temporal variation of the solar neutrino flux (above a threshold of perhaps 10 MeV), to searches for neutrinos from individual or the sum of all supernovae and other cataclysmic events (e.g. GRBs), to cosmic ray research (composition, where the CUNL depth is advantageous), dark matter searches (via annihilation neutrinos), searches for cosmic exotic particles (quark nuggets, glueballs,

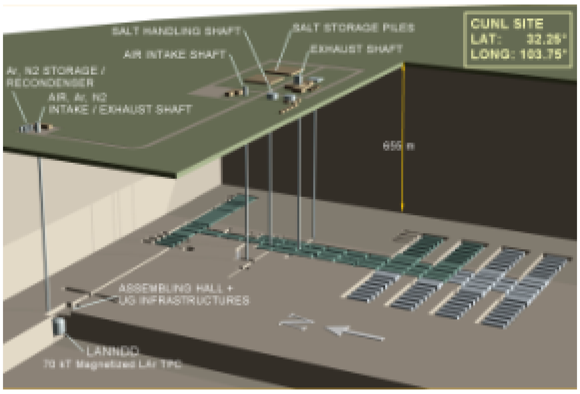

Fig.1. LANNDD at the CUNL site.

monopoles, free quarks), and point source neutrino astronomy. In all these instances, we can go beyond SK by virtue of lower energy threshold, better energy loss rate resolution, momentum, angle, sign and event topology resolution.

We note that in the "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" report (now in draft, 1/9/01, http://www.nas.edu/bpa/reports/cpu/index.html) for the National Academy, that such an instrument addresses eight of the eleven questions at least indirectly and of those eight, two explicitly (nucleon decay and neutrino mass)

2 The Carlsbad Site for LANNDD

In Figure 1 we show the possible location of LANNDD at the Carlsbad Underground Laboratory site (CUNL). Note that the ease of construction and the exhaust pipe are key motivations for this site. Safety would be accomplished by walling off the detector from the rest of the lab. Excavation is relatively inexpensive at this site due to the salt structure.

3 Some scientific goals of LANNDD

Much of the scientific studies that are being done with LANNDD follow the success of the ICARUS detector program[1, 2, 3]. The main exception is for the use of the detector at a neutrino factory where it will be essential to measure the energy and charge of the $\mu^{\pm}$ products of the neutrino interaction. We will soon propose an R&D program to study the effects of the magnetic field possibilities for LANNDD.

a) *Search for proton decay to 10^{35} years*

The detection of $p \rightarrow K^{+} + \bar{\nu}_{\mu}$ would seem to be the key channel for any SUSY-LUT model. This channel is very clear in liquid argon due to the measurement of the range and detection of the decay products. We expect very small background events at 10^{35} nucleon years for this mode (refer to ICARUS studies).

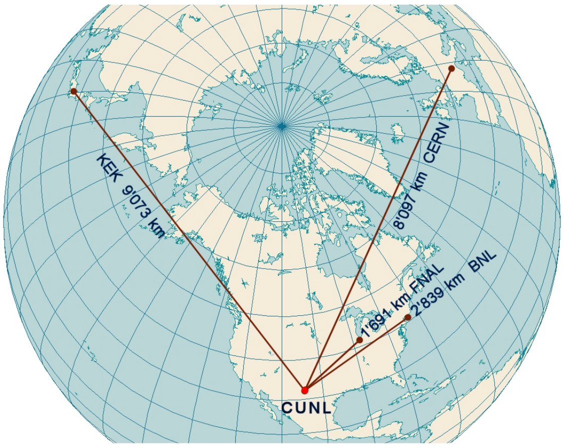

Fig. 2. Scheme of possible neutrino factory beams toward the CUNL site.

b) *Solar neutrinos and supernova neutrinos studies*

The major solar neutrino process detected in liquid argon is $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^{*} + e^{-}$, with K^{*} de-excitation giving photons with subsequent Compton events. The same process is useful for supernova ν_e detection – the expected rate for the solar neutrinos is ~123,000 per year. For a supernova in the center of the galaxy with full mixing there would be ~3000 events – no other detection would have this many clear ν_e events.

c) *Atmospheric neutrino studies*

By the time LANNDD is constructed it is not clear which atmospheric neutrino process will remain to be studied. However this detector will have excellent muon, hadron and electron identification as well as the sign of $\mu^{\pm}$ charge. This would be unique in atmospheric neutrino studies.

The rate of atmospheric neutrinos in LANNDD will be (50 kT fiducial volume):

CC ν_e events	4800/year
CC ν_μ events	3900÷2800/year

(depending on the neutrino mixing).

There would also be about 5000 NC ν events/year. We would expect about 25 detected ν_τ events/year that all would go upward in the detector.

Table 1
Long baseline beams at CUNL

LBL Beams	Distance	θ_H	θ_V
FNAL	1691 km	47.9°	7.8°
BNL	2839 km	62.5°	12.9°
CERN	8097 km	41.6°	39.5°
KEK	9073 km	-44.7°	45.4°

θ_H: angle, in the CUNL site horizontal plane, respect to the NORD
θ_V: angle, at the CUNL site, respect to the horizontal plane

d) *Use of LANNDD in a neutrino factory*

Because of the large mass and nearly isotropic event response, LANNDD could observe neutrinos from any of the possible neutrino factories: BNL, FNAL, CERN or KEK in Japan. There are two approximate distances $(2÷3)\times10^{3}$ km and $(7÷9)\times10^{3}$ km for these neutrino factories. We assume the more distant neutrino factories operate at 50 GeV $\mu^{\pm}$ energy. For a neutrino factory that produces 10^{20} $\mu^{\pm}$/year at FNAL/BNL we expect ~50,000 ν-interactions/year with right sign μ's (i.e. for $\mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu}$, the $\bar{\nu}_{\mu}$ gives μ^{+} as right sign muons). The number of wrong sign muons depends on the mixing angle θ_{13} (wrong sign muons are produced for $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$, with $\nu_e \to \nu_\mu$ and $\nu_\mu \to \mu^-$: the μ^- is the wrong sign muon) – there could be as many as 5000 wrong sign events/year.

For the farther distances (CERN, Japan) these numbers would be about the same due to the higher energy $\mu^\pm$ (50 GeV) with the rate increasing like the E_μ to the 3rd power.

The LANNDD detector could be useful for the search for CP violation from any neutrino factory location. This will depend on the value of the mixing angle θ_{13} and the magnitude of the CP violation.

For the longer distance experiments (CERN, Japan) there could be important MSW effect that is important to study in order to evaluate the significance of the CP violation search. It is possible that the electric charge of the $e^\pm$ from the reaction $\bar{\nu}_\mu \to \bar{\nu}_e$ could be determined as it was in heavy liquid bubble chambers by following the shower particles – this is currently under study.

In Figure 2 and Table 1 we show the schemata and parameters of neutrino factory beams to the CUNL site for detection by LANNDD – we consider this a universal neutrino factory detector.

4 The Detector

The aim is to build a 70 kT active volume liquid argon TPC immersed in magnetic field. The geometric shape of the detector is mainly decided by the minimization of the surface-to-volume ratio S/V, directly connected to the heat input and to the argon contamination. Spherical (diameter = D), cubic (side = D) or cylindrical (diameter = height = D) shapes all have the minimum S/V (=6/D). As compromise between easy construction and mechanical stability the cylindrical shape has been preferred. Adding to the S/V criterion the need of minimizing the number of readout wires (=electronic channels) and of maximizing the fiducial-to-active volume ratio, a single module configuration appears definitely advantageous with respect to multi-module array configuration (see Table 2). The more difficult mechanical design for the single volume configuration appears fully justified by the larger fiducial volume, the lower number of channels, the lower heat input and contamination and then lower construction and operating costs.

Table 2
Fiducial volume, number of channels and heat input (calculated with 1 W/m^2) for different detector configurations

	Single Module	*8 Modules*	*64 Modules*
Active volume, m^3	50000	50000	50000
Fiducial volume, m^3	41351	33559	21037
Number of channels	164261	337787	724077
Heat Input, W	9104	18209	36417

The internal structure of the detector is mainly relied to the maximum usable drift distance. This parameter depends on the acceptable attenuation and space diffusion of the drifting charges. Acceptable working conditions are obtained with an electric field of 0.5 kV/cm, a drifting electron lifetime of 5÷10 ms and a maximum drift of 5m. The detector appears then as sliced into 8 drift volumes, 5 m thick, each confined between a cathode plane and a wire chamber (Figure 3, 5).

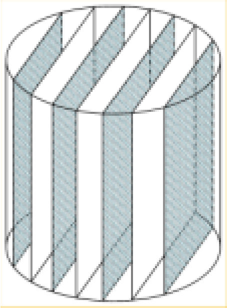

Fig. 3. Schematic layout of chamber (hatched regions) and cathodes planes (white regions).

Each wire chamber is made of 2 readout planes (x, y) with wires oriented at 0° and 90° (alternatively +45° and –45°) with respect to the horizontal plane. A 3 mm wire pitch gives a high definition imaging of ionizing tracks in the drift volumes (see first results obtained with ICARUS T600, Figure 4).

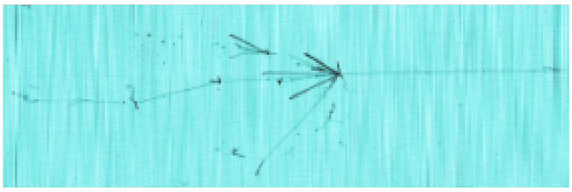

Fig. 4. Nuclear interaction in the ICARUS T600 liquid Argon TPC

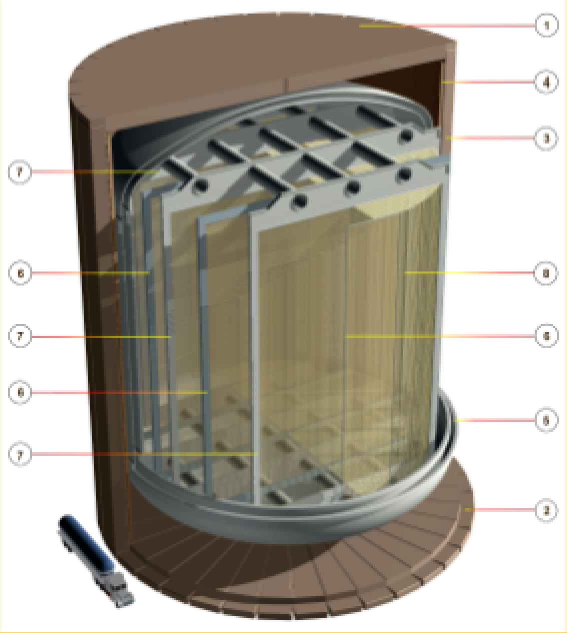

Fig. 5. Preliminary sketch for LANNDD: 1) Top end cap iron yoke; 2) Bottom end cap iron yoke; 3) Barrel iron return yoke; 4) Coil; 5) Cryostat; 6) Cathodes; 7) Wire chamber frames; 8) Field shaping electrodes.

The magnetic field is vertically oriented and is obtained with a solenoid around the cryostat containing the liquid argon. With such an orientation the maximum bending for a charged particle is obtained in a horizontal plane and appears in the imaging as an arc in each of the planes (x, t) and (y, t).

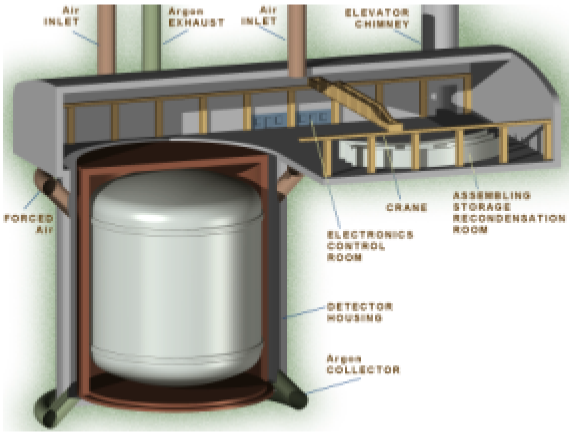

Fig. 6. LANNDD inside the underground cave.

The detector is foreseen as located underground at a depth of 655m (2150 ft) in a housing equipped with an emergency liquid argon pool and with argon vapor exhaust ducts. Forced fresh air inlet, liquid/vapor nitrogen in/out ducts, assembling hall with crane and elevator complete the basic organization of the underground cave (Figure 6).

As the difficulties of this project rely mainly on its engineering and safety aspects, a realistic mechanical design with costs and construction time estimates is matter of a dedicated feasibility study to be approved and properly funded.

For the full project definition a preliminary activity is required to study *a)* the imaging in a magnetized liquid argon TPC, *b)* the operation in conditions of high hydrostatic pressure, *c)* drift path of ≥ 5m.

References

1. ICARUS Collaboration, *“ICARUS-II. A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory”*, Proposal Vol. I & II, LNGS-94/99, 1994.
2. ICARUS Collaboration, *“A first 600 ton ICARUS Detector Installed at the Gran Sasso Laboratory”*, Addendum to proposal, LNGS-95/10 (1995).
3. F. Arneodo et al. [ICARUS and NOE Collaboration], *“ICANOE: Imagine and calorimetric neutrino oscillation experiment”*, LNGS-P21/99, INFN/AE-99-17, CERN/SPSC 99-25, SPSC/p314; see also A. Rubbia [ICARUS collaboration], hep-ex/0001052. Updated information can be found at http://pcnometh/cern/ch.