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Possible Study of Rare Decays of μ and Kaons and a Neutrino Near Detector with a Liquid Argon "ICARUS"-like Detector

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Introduction

The bubble chamber invented in the early 1950s by Don Glazer was one of the greatest advances in elementary particle physics. Combined with a magnetic field, full reconstruction of events such as the Ω^- was possible. Equally important in the history of the particle physics was the invention by David Nygren of the time projection chamber in the late 1970s for electronic track reconstruction. In this proposal we study the possibility of putting magnetic field on liquid Argon (LAr) time projection chamber (TPC) producing a "bubble chamber that is digitized for event reconstruction.

The CP violation in the Kaon sector also can be studied in such a TPC detector. An intense beam of both neutral and charged Kaons can be directed at the volume of liquid Argon TPC to study the ultra rare decay processes of stopping Kaons. One important rare process $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ has the branching ratio of 1.6×10^{-10}. Another is $K^{\circ}_{L} \rightarrow \pi^{\circ} + \nu + \bar{\nu}$. Our goal is to build a magnetized LAr TPC for detection of these rare processes. Future branching ratio measurements is to aim for the sensitivity to the $\sim10^{-14}$ level. In this proposal we discuss the work to study the use of MRI magnet coils for the study of the rare Kaon decays. We consider important also, the future magnetization of large scale liquid Argon TPC. This could be part of the Intensity Frontier development in the DOE and the NSF.

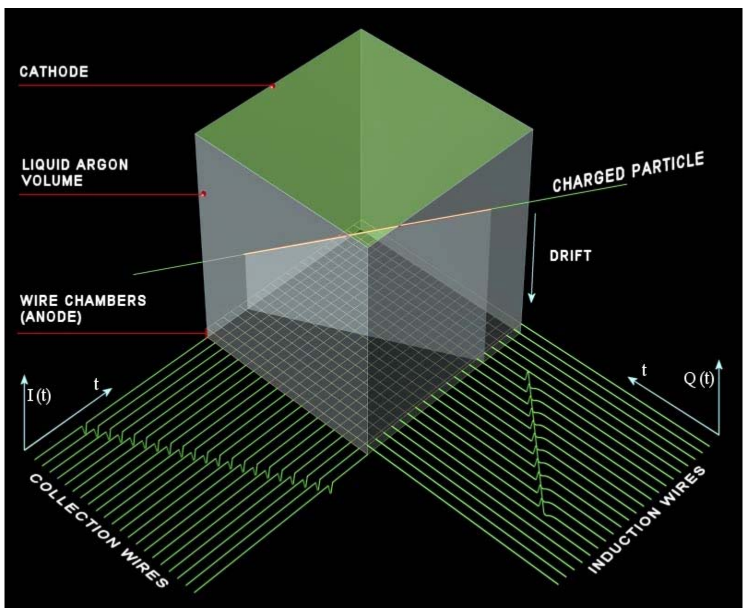


Figure 1. Basic description of the time projection chamber (TPC) with a wire chamber plane at bottom of a cubic cell The wire chamber plane has induction wire plane and a collector wire plane to construct the orthogonal coordinates, and the drift time of the electrons of the ionized track is used to construct the third orthogonal coordinate. The induction wires function as intrinsic signal differentiators and the collector wires as intrinsic signal integrators to be read using charge sensitive preamplifiers and current sensitive preamplifiers respectively [1].

The liquid argon time projection chamber

A massive detector can be built based on the liquid argon TPC technique. Such a technique has been developed and refined within the last two decades by the ICARUS collaboration and demonstrated in the ICARUS-T600 detector currently operating at the Gran Sasso Laboratory for over one year [2]. The LAr

TPC technique is based on an electrified parallelepiped LAr volume with one face occupied by a cathode plane and the opposite face by an anode wire chamber. The electric field E_d of 500 V/cm, in this "instrumented" volume, is maintained extremely uniform by surrounding it with a stack of equally spaced electrodes, set at linearly decreasing voltages from the cathode voltage to ground. Electrons generated by ionizing track crossing the LAr volume drift, under E_d, toward the wire chamber. See Fig. 1.

While approaching, crossing and leaving the first wire plane (wires at 0°) electrons induce a bipolar signal on the wires (*induction* signal). Due to an electric field $E_c \sim 1.5 \cdot E_d$ between the two wire planes, electrons escape the capture by the induction wires and drift toward the second wire plane (wires at 90°) where they are collected (*collection* signal) [1].

Signals generated in the two wire planes and drift time provide the 3-d information on each portion of the ionized track by generating a high definition 3-dimensional imaging of the track. The high definition of reconstructed tracks, together with the possibility of measuring the ionization intensity (*dE/dx*), allows for precise kinematic reconstruction and particle identification.

Description of a magnetized LAr TPC

The electrified parallelepiped volume of the TPC can be magnetized with a strong magnetic field to achieve event charge separation. A singly charged particle with 300 MeV/c momentum requires a 1 T field to deflect with a 1 m bending radius. The E_d field direction can be configured parallel or perpendicular to the *B* field direction depending on the available magnet. A higher resolution is achieved if the track bends in the direction of the TPC drift as in Fig. 2. In the perpendicular configuration, the electron drift velocity of 1.8 m/msec in a 1 T perpendicular field generates a negligible emf, only of 3.6% of the E_d field.

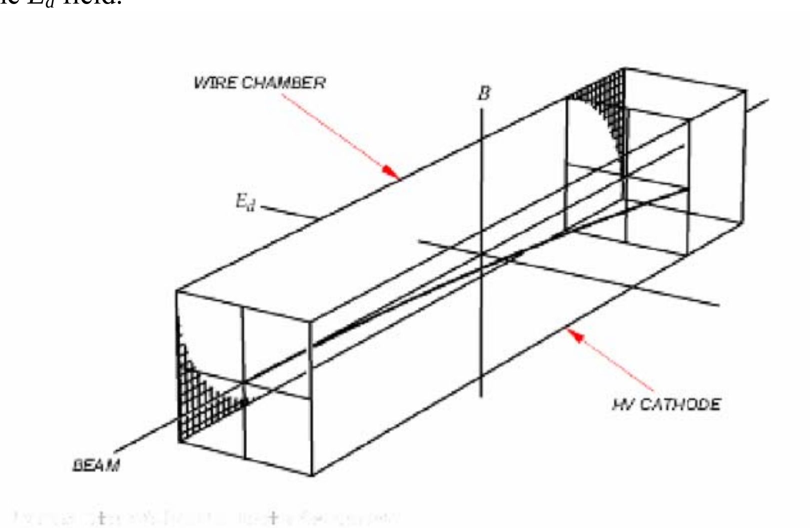


Figure 2. Magnetized TPC volume with the bending plane in the direction of the TPC electron drift, which has a higher position resolution than the wire pitch [1].

The method of magnetizing LAr TPC volume has been tested by A. Rubbia et al. in a small TPC of 15 cm dimensions in 0.55 T field [3]. Measurements of muon events presented in ~2005. For 3σ charge sign discrimination of muons, the B field is at least,

$$B \geq \frac{0.2}{\sqrt{x[m]}}[Tesla],$$

where x is the track length of charged particles. For a magnetic field of 1 T or higher, a track length of only 4 cm is required for charge separation. For momentum measurement, the precision is given as the following,

$$\frac{\Delta p}{p} \approx \frac{0.12}{B[Tesla]\sqrt{x[m]}}$$

where B is the field perpendicular to the motion and x is the track length. For a magnetic field of 1 T and track length of 1 m, the precision is at 12%.

An important application of the magnetized LAr TPC is found in the separation of charge current (CC) interaction of ν_e and $\bar{\nu}_e$ events which produce the electrons and the positrons, particularly for future accelerator based neutrino experiments. In the muon neutrino beam, the dominant component is of the muon neutrinos with smaller numbers of the anti-muon neutrinos and electron neutrinos with each having corresponding energy spectrum. Precision determination at the near detector of the electron neutrino flux and spectrum to a few percent levels is crucial to the measurement of the electron neutrinos at the far detector as well as the energy spectrum. We indicate here only that the MRI magnet with strong field can be used for charge separation in the near detector of the long baseline neutrino experiment.

The ICARUS –T600 detector

With the realization of the T600 detector the ICARUS collaboration finalized a pioneering long term activity on the development of LAr TPCs. The T600 detector is built of two equal sub-modules, each with an active argon volume of $18{\times}3{\times}3.2\ m^3 = 168.5\ m^3$, for a total LAr active mass of 472 Tons. Figure 3 shows the 3-D drawing of the ICARUS detector on left and the actual detector and the cryoplant on right. Figure 4 shows a CNGS high energy neutrino event in the 600 Ton.

The on-surface cosmic-ray test, made in 2001 on the first sub-module, has shown the high definition imaging and calorimetric capabilities of this kind of detector. From reconstruction and analysis of collected events during 3 months many published papers have been produced (see a selection in references 4-14).

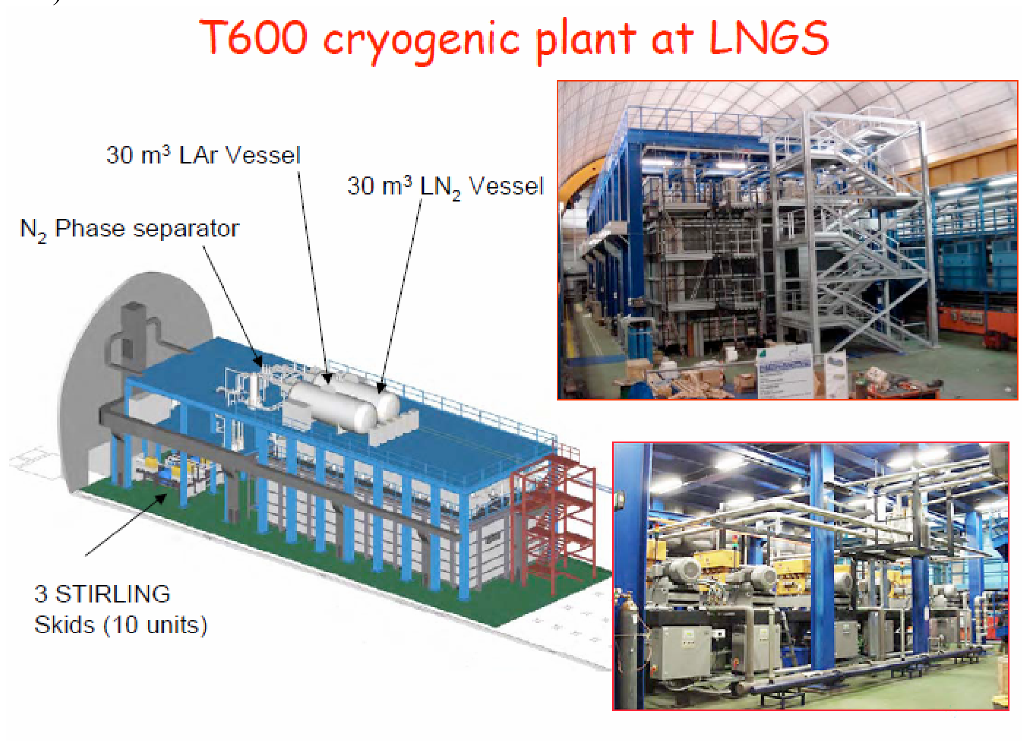


Figure 3. A 3D drawing of the ICARUS-T600 detector with its cryostat plant and photographs of the detector and its service stage in Hall B at Gran Sasso.

The ICARUS-T600 detector started in late May of 2010 the commissioning run in the underground Hall B of the INFN National Gran Sasso Laboratories (Italy). The UCLA group is actively collaborating in this project and took part in its design, test and data analysis of on-surface operation by taking the full responsibility in particular of the design, construction and operation of the T600 high voltage system.

The possible extension of the ICARUS detector to higher masses is planned to be done in the distant future by an array of several equal and independent T600-like modules.

ICARUS–T600 Events

With the recent start of the ICARUS-T600 commissioning run, the new era of high resolution event imaging in neutrino and cosmic ray physics has begun for the high energy particle physics community. Below in Figure 4 is a CNGS neutrino event that have been presented publicly [2]. The TPC detectors can detect tracks per channel at the rate of over ~10^3 Hz. In the ICARUS detector with each wire over a few meters length, signal pulse per wire has a capacitive time constant of ~ 400 nsec. A module of the T-600 twin was operated in early 200 on surface at Pavia in Italy capturing cosmic shower prior to transport to and installation at the Gran Sasso Laboratory. Technically, in this large scale detector with several ten thousand channels, the bottle neck will be at the multiplexing of the wire signals and in the electronics and transfer of the large event data size. UCLA is a member of the ICARUS event scan team.

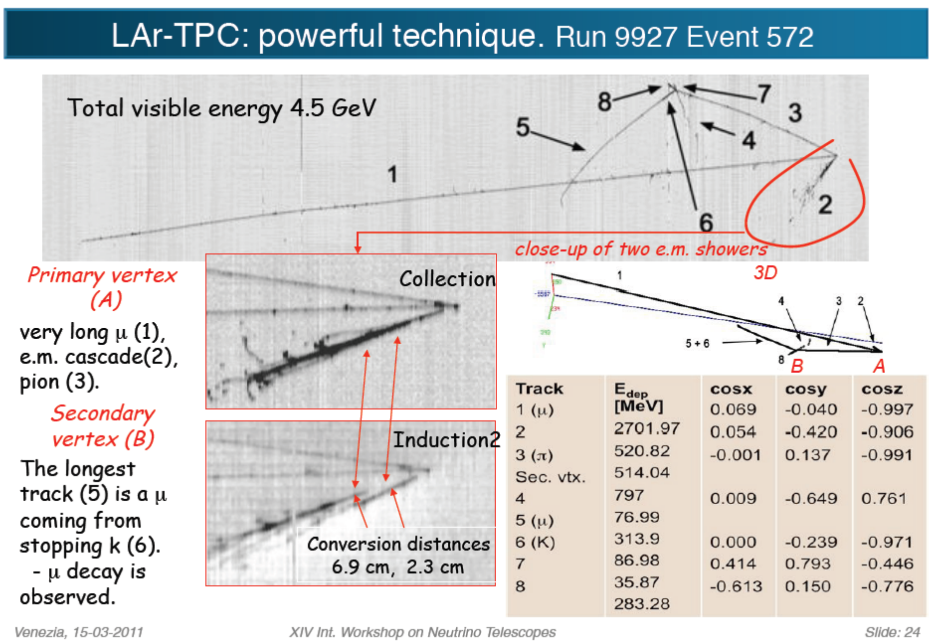


Figure 4. A high energy neutrino event from CERN detected in the ICARUS detector showing long muon track, a pion track and gamma showers[2].

Application to Kaon decay studies

Such a magnetized TPC can be used in the measurement of the rare kaon decay processes for the intensity frontier of the Project X now being developed in the DOE and the NSF. The lifetime of the charged kaons is only ~12.4 nsec while the charged pions 26.0 nsec. The momentum aperture of the beam can be controlled to allow the kaons to "stop" within a certain range of the magnetized TPC volume. The decay products can be measured well by a magnetic field of ~ 1 Tesla strength.

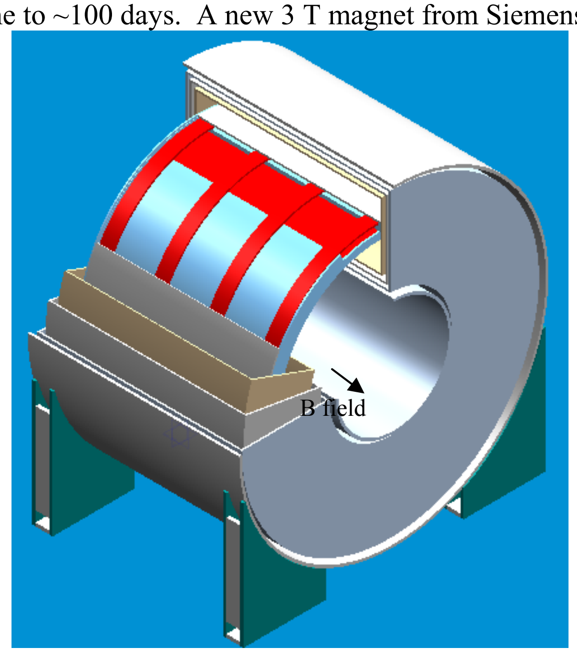
The Project-X is expected to have a very precise timing structure and to deliver ~100 MHz of kaons at the experiment. This requires tremendously fast detector response. The LAr TPC technology while is the best electronic bubble chamber to become operational in the near future, the imaging has a slower response. However, the experiment can be designed to incorporate the high resolution capability and the fast timing response of the Cerenkov light [7] and scintillation light using extremely fast photo-sensors that can operate in the high magnetic field environment. One important characteristic of the TPC is the continuous nature of the scanning that there is almost no dead time, apart from the wire responses. It is expected that there will be about 3 kaons per bunch every 30 to 40 nsec [4]. Also, there will be 1:80 ratio of pions. Due to the very short lifetimes, particle separation can not be achieved by time-of-flight. However, they can be identified by their different ionization track size in the liquid Ar especially when magnetized. Combining a battery of available fast timing information, much of the pion events can be rejected before having to study the associated image.

Magnetized LAr TPC in MRI Magnet

Magnetized LAr TPC has been considered by our group for charge separation of the electron neutrino interaction in one near detector system of the Long Baseline Neutrino Experiment (LBNE). We have considered magnetizing a LAr TPC volume of 2.5 m × 2.5 m × 2.5 m using a cubic coil wound with high temperature superconductor (HTS) wires but operating at ~20 K for cost effectiveness. In this work we will consider the 1.5 T MRI magnet. As many new higher field MRI magnets are becoming available in clinics, one may acquire one of the used magnet in the future phase for this detector development work.

The MRI magnet consists of the liquid He cryostat, the main magnet coil, the gradient coils, and the RF coils [5]. The main coil and some of the gradient coils are located inside the vacuum isolated liquid He reservoir. All currently available MRI magnets are made of low temperature superconducting (LTS) wires. All coils in the MRI magnet that are made of superconducting wires are to operate at the liquid Helium temperature of 4.2 K.

The magnet cryostat consists of the outer shell, the inner He reservoir, the central bore tube and the radiation shields at the two ends. We currently do not have detailed specification of the inner constructs of the cryostat. The inner construction will also vary between various models and manufacturers. For this short length model, the He reservoir can fill to a volume of ~800 liters, a scaled down estimate from the known He volume of 1,500 liter for a ~3 m long magnet. The reservoir is isolated from the outer shell radiation shields and the bore tube by vacuum, achieving good thermal insulation. There are cryo-coolers attached to the top of the outer shell that continuously pump heat out, extending the refill cycle time to ~100 days. A new 3 T magnet from Siemens has zero He boiled off.



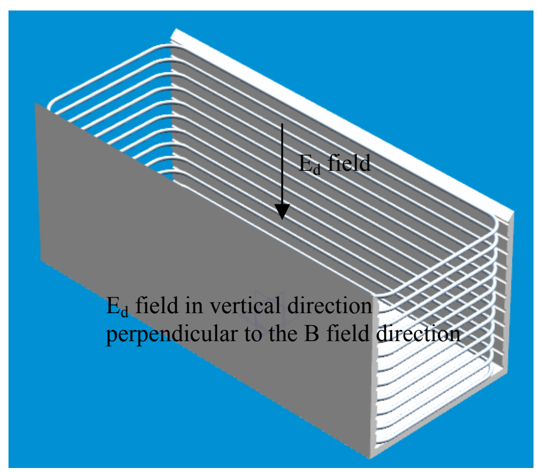


Figure 5. TPC structure is placed in the bore of the MRI magnet cryostat. The drawing shows the cryostat of 1.7 m long and 2.4 m diameter with 0.7 m bore diameter. The TPC structure is of long rectangular rings and PTFE boards with grooves for dielectric insulation. The TPC structure length shown is 1.4 m long. The wire planes not shown are to be of u, v, t configuration with 1 to 2 mm wire pitch for high resolution at top of the TPC structure.

For our application, the bore tube is to be modified into an Ar reservoir for the LAr TPC. The MRI magnets are designed to operate horizontally with symmetric distribution of the structural weight and magnetic forces. We will not attempt to modify any of the stability measures that affect the integrity of the original structural strength. We will design our LAr TPC to fit horizontally in the bore of the MRI magnet. The ends will be modified to allow for vertical tubes extending up from the central bore tube for feed through of the H.V. supply, the cryocooler cold head for the liquid Ar, and the signal wires. All the necessary modifications will conform to providing vacuum isolation for both the He reservoir and the Ar vessel (see Fig. 5).

For fast scanning response, the TPC structure is of rectangular parallelpiped shape to be positioned within the central bore of the MRI magnet. There will be 3 wire planes at top with the u, v, t readout. There will be a strong uniform voltage gradient in the drift direction perpendicular to the MRI magnet field. The TPC will be assembled of rectangular rings at pitch of ~5.1 cm. The H.V. cathode will at the bottom of the structure. The nominal drift voltage gradient is of 500 V/cm. Therefore, for a drift length of 52 cm, the H.V. is of 26 kV. With the extremely high voltages in the device, the H.V. feed through is necessarily well isolated and insulated at all point to prevent electrical discharge to ground. The detector will need to be designed to achieve towards the goal rate of 10^7-10^8 Hz. For rare decay processes this means that at least 10^{15} events/year could be processed.

Rare decay process and summary

The development of a liquid Argon detector in a large magnetic field could open up many particle physics projects. We already discussed a possible detector for $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$. Other rare processes like $\mu^+ \rightarrow e^+ + e^+ + e^-$ could be considered. The excellent charge and vertex identification in a magnetic field could be a key. One might even study CP violating process $K_L \rightarrow \pi^\circ + \nu + \bar{\nu}$. One might even attempt to measure the extremely rare process $K_L \rightarrow e^+ + e^-$ without any neutrinos in the decay.

The development of a magnetized liquid Argon TPC could have a large future impact. It could lead into also magnetization of much larger volumes in the future long baseline neutrino detectors. While we cannot envision ultra high field of several Tesla in the large neutrino detector, it maybe possible to develop program for magnetization of the entire cavern using superconducting loops with built in cryostats, especially with the recently developed high temperature superconductor (HTS) cable for power transmission. Such idea has been preliminarily studied at the Fermilab.

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