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IDEAS IN NEUTRINO PHYSICS[*]

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The ideas in neutrino physics are both, exciting and instructive. In this paper, a subjective review of several fundamental ideas and discoveries in this subject will be presented. We will focus on experimental aspects, starting from the discovery of electron neutrino, about 20 years after neutrino "theoretical birth" by W. Pauli, and finishing with short status of current techniques used in large scale neutrino physics experiments.

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1. Introduction

The neutrino came first as a hypothesis, then was introduced into the theory, and finally was discovered in the experiment. In 1930, W. Pauli, in his famous letter to physicists participating in the Tübingen nuclear physics conference, proposed the existence of a new particle to solve two problems: (1) continuous electron spectrum in what in that time was believed to be a two-body β decay, and (2) wrong values of spin of some nuclei. As we know, Pauli's hypothesis appeared to be right, however, he was wrong saying *I have done something very bad today by proposing a particle that cannot be detected. It is something no theorist should ever do.* In 1934, E. Fermi [1] presented the first theory of the nuclear β decay. He proposed that two spin 1/2 particles, electron and neutrino, are emitted from a nucleus which consists of other spin 1/2 particles, proton and neutron. So, it was a point-like interaction of four spin 1/2 particles. During this process a neutron *becomes* a proton via quantum transition. It took about 20 years to prove Pauli's hypothesis and Fermi's theory. In 1953, Reines and Cowan, in their famous experiment [2], observed the inverse β decay process. Electron antineutrinos from the Savannah River reactor interacted with protons of a liquid scintillator target loaded with $CdCl_2$ producing neutrons and positrons. Neutrons

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were slowed down and captured by Cd resulting in emission of a *slow* γ, whereas two *fast* γ's, emitted in opposite directions, resulted from positron annihilation. In 1957, B. Pontecorvo, in analogy to the oscillations in the kaon system, put forward an idea of neutrino–antineutrino oscillations for Majorana neutrinos [3]. In 1962, Z. Maki, M. Nakagawa and S. Sakata discussed oscillations between two neutrino flavors, being a mixture of two mass states [4]. In 1969, Gribov and Pontecorvo presented the first phenomenological theory of two neutrinos mixing [5], which explained results of many neutrino oscillation experiments performed later on. Due to the extremely low cross section of neutrino interactions, neutrino experiments are actually searching for rare phenomena. Therefore, they have to fulfill several requirements: (1) the detector has to be large/huge, (2) the neutrino source/beam has to be very intense, (3) the background has to be extremely low, for example an experiment performed underground reduces considerably cosmic rays induced background, and (4) the measurement has to be sufficiently long to deliver conclusive results. Some ideas in neutrino physics along these requirements will be presented in this contribution.

2. Idea of Gran Sasso underground laboratory — LNGS

In 1979, A. Zichichi presented the Gran Sasso project to the Commission of Public Works of the Italian Senate (see Fig. 1). The scientific objectives were studies of: (1) nuclear stability, (2) neutrino astrophysics and oscillations, (3) new cosmic phenomenology, (4) biologically active matter, and

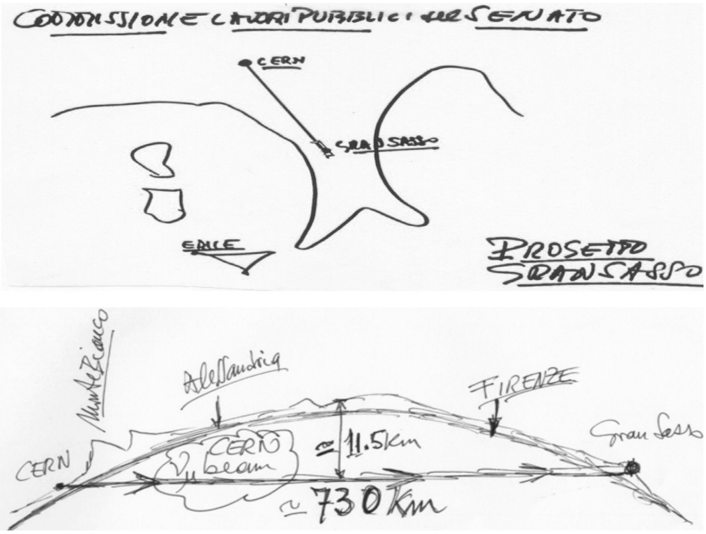

Fig. 1. Handwritten A. Zichichi notes from his presentation to the Commission on Public Works of the Italian Senate [6].

(5) ground stability. His presentation resulted in an increase of the INFN five-years budget by a factor 10. The laboratory has been constructed in next years, with main excavation completed in 1987. Some vital safety upgrade was accomplished in 2007. The *Laboratori Nazionali del Gran Sasso* (LNGS) is presently the largest underground laboratory in the world with underground area of about 17 000 m^2 in three main experimental halls. The variety of neutrino experiments account for the main physics program at LNGS.

3. Idea of Liquid Argon Time Projection Chamber — LAr-TPC

In 1977, Rubbia [7] conceived the idea of a LAr-TPC, which allows a 3D imaging of any ionizing event, like a bubble chamber based detector. Therefore, it offers high granularity (1 mm), excellent calorimetric properties and particle identification through the dE/dx *versus* range measurement. However, contrary to the bubble chambers LAr-TPC is an electronic detector, which is continuously sensitive and self-triggering. Electrons from ionizing track are drifted in LAr by electric field from cathode to anode wires. In the ICARUS T600 cryogenic detector, the biggest LAr-TPC realized ever, the electrons traverse two almost transparent anode wire arrays oriented in different directions where induction signals are recorded. Finally, the electron charge is collected by the third collection plane of anode wires. The key feature of successful operation of any LAr-TPC is liquid argon purity from electro-negative molecules, which has to be kept at the level of 0.1 ppb

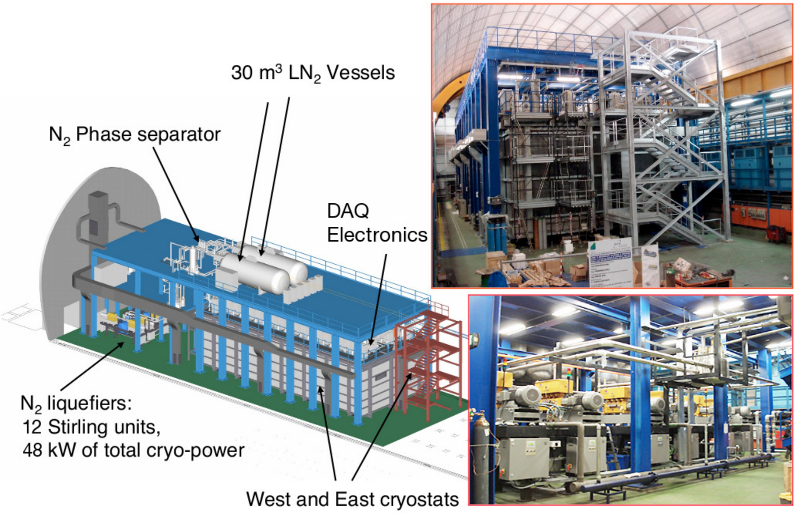

Fig. 2. Schematic view of the whole ICARUS T600 plant in HALL-B at LNGS. Right-top: photo of the actual detector installation. Right-bottom: details of the cryocooler plant (from [8]).

O_2 equivalent, resulting in 3 ms electron lifetime allowing a 4.5 m long drift distance in an electric field of 500 V/cm. The ICARUS T600 is now installed in the Hall-B of the LNGS (see Fig. 2). It is running smoothly under stable conditions for many months (since October 2010), being a major milestone in the practical realization of large-scale LAr detectors.

4. Ideas of next generation neutrino detectors and neutrino beams

Neutrinos oscillate and, therefore, they mix and have non-zero masses. This is a very important result delivered by several experiments in the last two decades. However, few fundamental questions, such as neutrino mass hierarchy, the absolute mass scale or CP violation in the lepton sector still remain open. It is common to believe, that to answer the last two will require next generation of neutrino detectors and neutrino beams. The next generation detectors are considered as an extrapolation of the existing liquid based neutrino detectors. Three liquids, namely, water, liquid scintillator and liquid argon are presently in use and can be scaled to much higher masses/volumes [9]. The neutrino super beam will be a conventional beam (neutrinos originate from pion/kaon decays) but with much higher intensity of 1–2 MW. This option is considered as a short-term one, which can resolve the neutrino mass hierarchy problem. Whereas, neutrino beta-beam (accelerated radioactive ions decaying into electron antineutrinos or electron neutrinos) or neutrino factory (muon/antielectron or antimuon/electron neutrinos originating from negative and positive muons decay in the straight sections of a muon storage ring), are much longer term options.

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