WILL FINLAND BECOME THE CENTER OF EUROPEAN NEUTRINO PHYSICS?

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European plans for the construction of a deep underground science facility for neutrino physics and proton decay are presented and discussed. The new facility should host a very large volume neutrino detector of the next generation that would work also as a far detector for the very long baseline flavor oscillations with neutrino beams from CERN and possibly also from Protvino. The Pyhäsalmi mine in Finland is currently the strongest contender.

Introduction

Neutrinos are the only particles known to disobey the predictions of the Standard Model. Over the past two decades neutrino studies have produced a wide range of important data and new discoveries: neutrino oscillations, evidence for non-zero neutrino mass, detection of supernova and geo neutrinos, spectroscopy of solar neutrinos, and so on.

These findings, in turn, stir up expectations of a major breakthrough in physics that could have similar impact on science as the quantum theory and relativity brought about a century ago. The importance and relevance of the neutrino physics was very well illustrated by the recent race to measure the missing oscillation parameter (θ_{13}). Although the costs and complexity of the required experiments is very high, five major experiments (T2K [1], MINOS [2], Double Chooz [3], Daya Bay [4] and Reno [5]) have embarked on this fierce race and all have published their first, preliminary θ_{13} values within the period of nine months (Fig. 1).

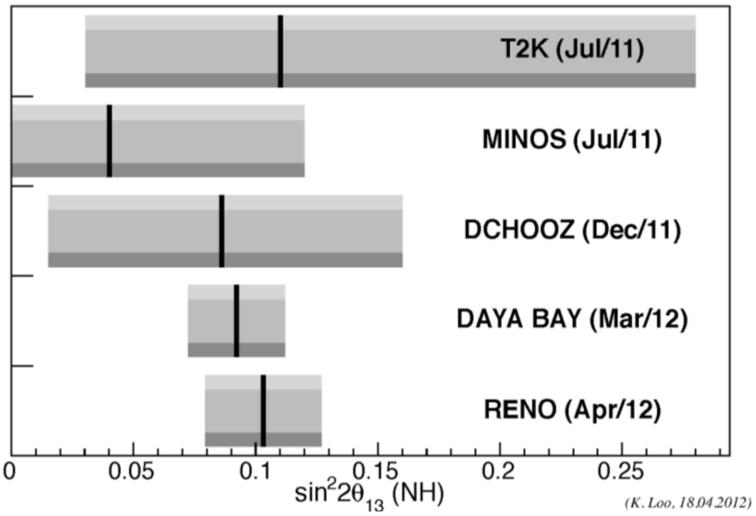

Figure 1. The first, preliminary values for the missing neutrino mixing parameters. Name of the experiment and publication date is listed next to each result. The width of each bar indicates error margins.

Already now a new race has started for the determination of the neutrino mass hierarchy and the phase of the CP violation in the leptonic sector. In Japan designs are made for Hyper Kamiokande experiment that would increase 25-times the size of the highly successful SuperK [6] water Cherenkov detector. The Americans have recently (December 2012) crossed a significant milestone when the U.S. Department of Energy granted Critical Decision 1 approval to the first phase of LBNE (Long-Baseline Neutrino Experiment). It includes construction of a beamline at Fermilab and a near-surface far detector at the Sanford Lab in Lead, South Dakota. In China preparations are being made for the next phase of the Daya Bay experiment. Plans are drawn for a 20 kton liquid scintillator detector to be build at the distance of about 60 km from the powerful reactor complex. Independently, experiments utilizing PBq – strength radioactive sources are considered to verify the hypothesis of sterile neutrinos. LAGUNA-LBNO (Large Apparatus studying Grand Unification and Neutrino Astrophysics [7] – Long Baseline Neutrino Oscillations) is the European answer to this global challenge. A consortium of 300 scientists and engineers from 13 countries is currently making plans to build in Europe a new, deep underground science facility for neutrino physics and proton decay. The facility would host a very large volume neutrino detector of the next generation that would also work as a far detector for the very long baseline flavor oscillations with neutrino beams from CERN. The Pyhäsalmi mine in Finland is the strongest contender for the location of this mega-project.

Site investigations

Seven European sites were proposed to host LAGUNA. All of them were thoroughly investigated as part of an FP7 Research Infrastructure Design Study. The 1.7 M€ LAGUNA grant (Grant Agreement No. 212343 FP7-INFRA-2007-1) was utilized over the period 2008 – 2011. Among the seven investigated sites four were located in mines: Pyhäsalmi in Finland, Boulby in the UK, Sieroszowice in Poland, and Slanic in Romania; two were attached to an operating road tunnel: Fréjus in France and Canfranc in Spain; and one – in Umbria region of Italy – was a virgin site with no existing infrastructure.

The main outcome of the Design Study is that the giant caverns required by LAGUNA detectors are technically feasible and relatively cost effective. The price tag for excavation and preparation of the underground space is in the range of 10 – 20% of the total costs. Since, in principle, all sites were found to be technologically suitable to host LAGUNA, the main selection criteria were driven by physics arguments [9]. Nevertheless, since the construction time and costs have to be minimized, the quality of the rock and the available infrastructure remain high on the priority list in choosing the best site.

Advantages of the Pyhäsalmi site in Finland

The strength and uniqueness of the Finnish site is that it fulfills simultaneously all the key requirements, both from the physics program of LAGUNA and from the engineering point of view. Here is a short list of the main properties characterizing the Pyhäsalmi mine:

- Excellent quality of the surrounding rock; the best among the investigated sites and one of the best in the world.

- One of the deepest and coolest locations in Europe (+22 C and dry at 1400 m ≈ 4000 m.w.e). The importance of a large overburden for reducing the flux of cosmic muons and the associated neutron background is self-evident, especially for the scintillator detector. The low ambient temperature guarantees not only comfortable working conditions but also reduces or eliminates the need for cooling thus lowering the construction and operation costs.
- The distance from CERN (2300 km) offers unique long baseline opportunities, not found elsewhere in Europe or in the world. This is especially relevant for Mass Hierarchy determination. Recently decisions were taken in Russia to increase funding for the accelerator center in Protvino near Moscow. As one of the main scientific goals a proposal was made to produce neutrino beam and aim it towards Pyhäsalmi (1160 km) as shown on Fig.2. Both at CERN and at Protvino the construction of a beam towards Finland would not require the enlargement of the laboratory grounds, as there is just the suitable space available in the desired direction. LAGUNA is currently evaluating the benefits of such a double beam and its impact on systematic errors and sensitivity to CP violation.
- The lowest reactor neutrino background in Europe [9]. This requirement is important for the scintillator option and especially for the study of geo neutrinos [10].
- Two modes of access: via shaft and decline. The shaft gives the shortest and the fastest access for personnel and small equipment; the decline enables truck deliveries of everything else. In addition, there are direct pipelines from the surface for the delivery of water, fuel, and concrete.
- Ample space on the surface for storage and construction of new facilities. Good road and railroad connections.
- Infrastructure in perfect condition. Pyhäsalmi is one of the most modern and mechanized mines in the world!
- Ore deposits in Pyhäsalmi have an unusually small footprint. As a result, unlike in the other mines, the tunnel network is very small and concentrated tightly around the decline. Since there is also no water problem, the maintenance costs are small.

- Perfect coincidence between the expected end of excavations (~2018) and the proposed start of the LAGUNA instrumentation phase.

Excellent cooperation between scientists and the mine management. For well over a decade the mine has been hosting Center for Underground Physics in Pyhäsalmi (CUPP) [11] – a scientific unit managed by the University of Oulu and operated jointly with the University of Jyväskylä and a number of international collaborators from Russia and Denmark. The main activity of the Center is EMMA [12] – an experiment dedicated to the study of composition of the cosmic rays.

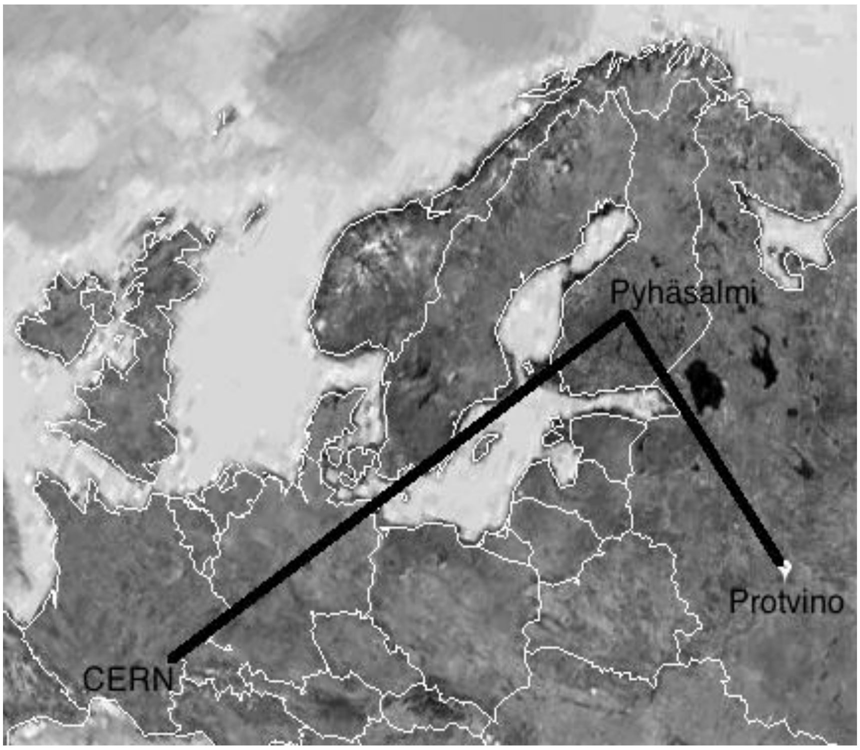

Figure 2. Location of the Pyhäsalmi mine with respect to CERN (CH) and Protvino (RU). The length of the corresponding baselines is 2300 km and 1160 km.

Considered detector technologies

There are three detector technologies considered by the LAGUNA collaboration for the main detector. They are based on three different liquids: argon (at -186°C), scintillator (doped synthetic oil), and water (ultra pure). The liquid argon detector is often referred to as GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment) [13]. The liquid scintillator detector is nicked named LENA (Low Energy Neutrino Astronomy) [10] and the water Cherenkov option is known as MEMPHYS (MEgaton Mass PHYSics) [14]. To a great extend these are complementary technologies so implementing them simultaneously would have the larges science impact. However, considering the financial implications, this is not likely to happen. Instead the collaboration is expected to come up with a prioritized recommendation list based on the scientific, technological and economic grounds.

Water Cherenkov

SuperK – the biggest currently operating neutrino detector [6] – is a 50 kton tank filled with purified water and instrumented with 11,146 Hamamatsu Type R3600 50 cm diameter hemispherical PMTs detecting Cherenkov light emitted by relativistic charged particles produced within the active volume. The excellent performance of SuperK suggests water Cherenkov technology as a natural choice also for the next generation of neutrino detectors. However, to achieve a substantial improvement in performance, the successor would have to be considerably larger and therefore also significantly more expensive and technologically challenging. The other limitation of the water Cherenkov (WCh) technology is a relatively high registration threshold (about 2 – 6 MeV; depending on the photocathode coverage). This limits the use of WCh for astroparticle applications. Also, poorer performance of WCh for very high-energy events reduces its usefulness as a far detector in neutrino oscillation experiments at very long baselines when the required energies of neutrino beams are well above 1 GeV. Nevertheless, WCh remains one of the three key options for LAGUNA. This option would be especially relevant if CERN would make a commitment for the production of beta-beams towards Frejus. There are also ongoing attempts to enhance physics capabilities of WCh beyond that demonstrated by SuperK. The main development is to improve neutron capture probability by adding gadolinium (Gd) salts to the water [15]. The benefit of gadolinium loading is threefold. It increases the probability of neutron capture, extends the total energy of the subsequent gamma cascade from 2.2 MeV, as it is in the case of free protons from water molecules, to 8 MeV, and reduces the mean lifetime of a neutron in the liquid from around 200 μs to about 30 μs. While a 2.2 MeV gamma induced event is practically below the detection threshold of a WCh an 8 MeV cascade, providing adequate photocathode coverage, would give a clear signal with a good background rejection thanks to the reduced correlation time. The minimum desired overburden for MEMPHYS is 3000 m.w.e. (1100 m of rock). The strongest advantages of MEMPHYS are the well-proven, robust and environment friendly technology, lowest cost per mass unit, and the largest proposed fiducial mass.

Liquid Scintillator

The concept and the basic construction of a Liquid Scintillator detector (LSc) is very similar to that of WCh. Most of the virtues of LSc originate from a ~50-fold increase in the light output as compared to a water-based detector. As a result LSc detectors have good energy resolution, low threshold, excellent background discrimination, and may be considerably smaller from their WCh equivalents. Indeed, all of the operating LSc detectors including KamLAND [16], Borexino [17], and SNO+ [18] have fiducial mass below 1 kton. It should therefore be relatively straightforward and cost effective to build a neutrino detector of the next generation by increasing the scintillator mass without the need to excavate caverns much larger than that used by SuperK [6]. This is the path chosen by LENA [10]. The main difficulty will be to increase the size and maintain the level of radio purity achieved so far only by BOREXINO – the smallest of the large LSc detectors. Because of the limited transparency of the scintillator, a 2 x 14 m = 28 m restriction should be applied either to the height or to the diameter of the cylinder defining the fiducal volume of LENA. Until recently lack of tracking was considered the most serious drawback for LSc. This is no longer the case [10]. The latest simulation studies confirmed by analysis of BOREXINO data indicate that LENA would make a good choice for a far detector in Pyhäsalmi. The sensitivity of a 50 kton LENA to Mass

Hierarchy determination is comparable to that of a 20 kton GLACIER. The minimum required overburden for LENA is 4000 m.w.e. (1400 m of rock). The main advantages of LENA are the lowest energy threshold, proven technology and the smallest total cost.

Liquid Argon

GLACIER [13] proposes by far the most advanced detection technology of all LAGUNA detectors offering impressive tracking abilities and sophisticated background rejection. With the target mass that may reach up to 100 kton of liquid argon it would be the best far detector ever build for neutrino oscillation studies and an excellent tool for high-energy astroparticle physics and the search for proton decay. Unlike MEMPHYS and LENA, GLACIER may be located at a moderate depth. The required overburden is a modest 2500 m.w.e. (900 m of rock). The biggest challenge for GLACIER is the detector technology that although is rapidly developing but it is still in an early stage. The largest operating LAr detector is ICARUS T600 [19] with only 480 ton contained in the sensitive volume. It uses only single (liquid) phase both for tracking and readout while GLACIER intends to use both the liquid and gaseous phase and benefit from gas amplification of the signals while reaching the longest possible drift length of 20 m. To cope with that great challenge and with the rapid technological developments the current strategy for LAr foresees an incremental approach that would slowly build up the size. At first a small prototype would be build followed, if all goes well, by a 20 kton unit. The final conceivable step would be a 50 kton detector.

Conclusions and outlook

It is clear that neutrino physics will continue dominating physics agenda during the coming years. What is not clear is the degree of EU participation in this work. Will the governments and funding agencies be sufficiently farsighted and courageous to support a major European research effort in the field of neutrino physics? Will Finland accept the challenge and responsibilities of hosting the first large international program in her history? Will CERN commit resources to build and maintain a new neutrino super beam and work towards neutrino factory? The main goal of LAGUNA and LAGUNA-LBNO design studies is to provide the necessary input for such decisions and to find the optimal path toward its realization. Starting from the groundbreaking works of Bruno Pontecorvo and his coworkers till the collapse of the Soviet Union, Russia has played a key role in neutrino physics; both theory and experiment. By taking a major responsibility in LAGUNA Russia would be able to reclaim her lost role in that field and help attract to it other countries inside and outside of Europe. The fact that the Finland is the primary choice for the deep underground laboratory and that Pyhäsalmi is just a car drive away form St. Petersburg adds an important geo-political argument for Russia to get involved. The option of Protvino beam, proximity to major industrial centers able to supply both the synthetic oil and liquid argon, and Russian expertise in detector technology provide additional reasons. There would be further synergy if the LSc option would be build. In addition to the beam studies and astroparticle measurements LENA would allow oscillometric studies to search for and study the properties of sterile neutrinos using enriched radioactive sources produced, for instance, in the new PIK reactor in Gatchina.

To summarize, there are firm reasons to believe that LAGUNA offers the safest path towards the new era of neutrino measurements that are likely to bring a major breakthrough in physics. Let us do our best to help make it happen.

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