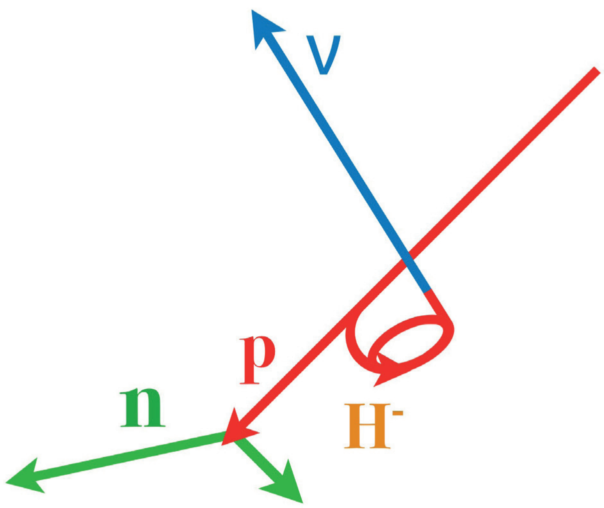
Challenges and Opportunities

The ESS Neutrino Super Beam Project



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Industry and science share a common approach – *going from a sound idea to a useful product or solution requires many different thought processes and a large dose of perseverance in the face of real life adversity*. Meeting this challenge enables industry to produce the finest quality products and solutions and for scientists to make breakthrough discoveries. Due to this, we are confident that you will give consideration to this proposal for a project that will produce several breakthrough discoveries and view it as a worthwhile arrangement as an industry- science partnership.

EXECUTIVE SUMMARY

There is no more noble enterprise, and none provides more gratification, than the exploration of nature at its deepest levels - and the investigation of neutrinos is at the core level. Neutrinos originate naturally, such as from cosmic rays, but in natural form they don't have the characteristics to subject them to study in coherent ways. This project solves that problem.

The European Spallation Source (ESS), currently under construction in Lund, will be the world's most intense source of accelerator-generated neutrons and the Neutrino Super Beam project (the subject of this proposal) will use the ESS accelerator to purposefully produce neutrinos in abundance in addition to, and simultaneously with, neutron production. This will result in the most intense neutrino beam in the world and open pathways to wide-ranging discoveries. These discoveries will unlock secrets of the universe as well as providing practical industry applications.

Projections for upgrading the ESS to enable the Neutrino Super Beam have already been studied and an interim budget of € 5.2 million has been secured. Now, we need funding to cover test drilling of holes, design and construction studies and equipment, all detailed below. To cover this, we are seeking contributions from enlightened, forward-thinking companies who want to fortify their corporate responsibility profile by being a part of this exciting project. In recognition of this support, your company will receive access on a gratis basis to theoretical and experimental physicists and engineers to help solve a problem that might be perplexing your company (even non-physics problems), a name plate on equipment of the Super Beam project, and recognition in our publicity and promotional materials. Your company will also be able to promote its contribution in its advertising and promotional materials. Overall, a company can be gratified by supporting one of the most important scientific experiments on the planet.

1. Introduction

Neutrinos are of interest to physicists for some of the same reasons that pottery shards are interesting to archaeologists. Just as archaeologists study broken clay pieces to construct a story about the society that produced them, physicists examine neutrinos to learn more about the events and processes from which these sub-atomic particles have their origins.

Nature produces neutrinos in several ways. The Big Bang produced neutrinos — ghostlike particles that are still zooming through space even today. Atomic power plants also produce neutrinos. Similarly, the furnace of our Sun pumps out neutrinos. When a star goes supernova, the process generates an enormous burst of neutrinos.

Nobel Prize winner Wolfgang Pauli first suggested the existence of neutrinos in 1930 to explain what was at the time a strange feature in the observed electron energy distribution in radioactive decay. The first direct observation of neutrinos was made in a U.S. reactor experiment in 1956 by Frederick Reines (Nobel Prize in Physics 1995) and Clyde Cowan.

There is, however, more to neutrinos than just the debris of reactions; they are interesting in their own right. They almost never interact with matter, rendering neutrinos a challenge to study. They come in three "flavours"— electron, muon and tau. They oscillate — change flavours — in mid-flight. Oscillation is like imagining a sports car changing into a bus as it goes down the highway, then changing back again to a sports car. It gets even more complicated. Neutrinos have mass (just barely), but the mass and the flavours don't necessarily correspond. Particle physicists talk about *mixing* to describe the weird morphing of neutrino masses and flavours; the mixing phenomenon is the focus of many neutrino experiments.

Physicists have long understood that one path to learning more about almost any aspect of energy or matter leads, sooner or later, through a cloud of neutrinos, the mysterious and ubiquitous subatomic particles. We have learned a lot about stars (including our own Sun) by studying neutrinos, and there is a lot more to learn about the cosmos using neutrinos. Understanding galaxy clustering or why the universe is dominated by matter and not anti-matter requires a deeper knowledge of how neutrinos behave. This is essential to taking a number of next steps beyond current physics.

2. New Practical Technologies

This invisible and almost massless particle, having the potential to reveal amazing things, could be the building block for some novel technologies. Neutrinos could be used for:

- Monitoring nuclear proliferation.

Neutrinos are produced in radioactive decay, so it is possible for the International Atomic Energy Agency to use neutrino detectors to monitor which countries are not following the treaty on the Non-Proliferation of Nuclear Weapons.

- X-raying the Earth to find cavities of mineral and oil deposits.

Neutrinos can be used to image deep underground inclusions of differing densities in the Earth's crust. Among the deposits that can be investigated are heavier mineral deposits, oil deposits, water cavities, iron-banded formations, and regions of abnormal charge accumulation that have been posited to appear prior to the occurrence of an intense earthquake.

• Exploring the source of heat in the interior of planet Earth.

The processes in the Earth's interior, in particular the role played by nuclear decay, are still poorly understood. However, the neutrinos from nuclear decay can be detected at the surface of the Earth and provide information about the processes that control how heat inside the Earth is generated and maintained. This is very relevant to an understanding of global climate.

• Faster global communications.

• Neutrinos can pass through just about anything and, if you send a message, say from the U.S. to China on the other side of Earth, it would be faster to send the message through Earth rather than over it. Using neutrinos would also be a way to communicate with submerged submarines. It has already been proven that it's possible to encode a message in neutrinos using binary code. In the image below, (a) is how scientists formatted the message and (b) is what the message looked like to the sender and receiver.

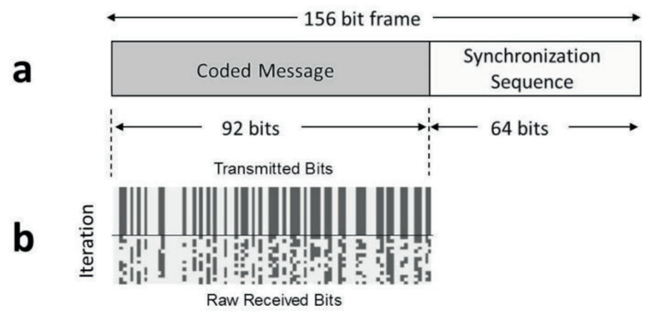


Fig. 5. Format and representations of transmitted data. (a) Frame structure of the transmission. (b) Depictions of the transmitted and received data.

• Detecting dark matter – a Holy Grail in physics.

Roughly 80 percent of the mass of the universe is made up of material that cannot be directly observed. Over a hundred years ago studies of the movements of stars in the Milky Way provided first indications that the universe contains more matter than seen by the naked eye. Known as Dark Matter, this bizarre ingredient does not emit light or reflect light, but the motions of stars tell us that it must be there due to gravitational effects. Dark Matter particles have still not been directly observed, but neutrinos could provide the missing link. Dark Matter could be detected indirectly through the observation of neutrinos produced in Dark Matter self-annihilations or decays. Dark Matter could also consist of heavy neutrinos, partners to the three light neutrinos that we already know of. The existence of such heavy neutrinos could be inferred from, or directly observed in, future experiments.

• Exploring the cosmos at very large distance.

A large neutrino detector, Ice Cube, which is installed in Antarctica, has recently observed extremely high-energy neutrinos which are thought to have originated in distant galaxies. These neutrinos could thus carry important information about these very distant galaxies, thereby complementing information obtained from the direct observation of these galaxies.

3. THE ESS SUPER BEAM – a plentiful source of neutrinos

The European Spallation Source (ESS), currently under construction in Lund, will be by far the world's most intense source of accelerator-generated neutrons. The total ESS construction budget is € 1.84 billion, of which Sweden is contributing 35% and the remaining 65% by 10 other European nations. The spallation neutrons will be generated using a superconducting linear proton accelerator of 2 GeV energy and 5 MW average beam power, making it the world's most powerful proton accelerator. The proton beam is delivered in 14 pulses per second each of 2.84 ms length, meaning that the accelerator radio frequency power generators, which deliver 125 MW of peak power, are active only 4% of the time.

Through the Neutrino Super Beam project, we propose to increase the number of pulses in the ESS linear accelerator to 28 per second, which will require the power generators to be active 8% of the time, thus increasing the average beam power to 10 MW, and to use the added beam pulses to simultaneously generate a beam of neutrinos. With this use of an additional 5 MW, the ESS neutrino Super Beam will become the most intense neutrino beam in the world and open the pathway to remarkable discoveries.

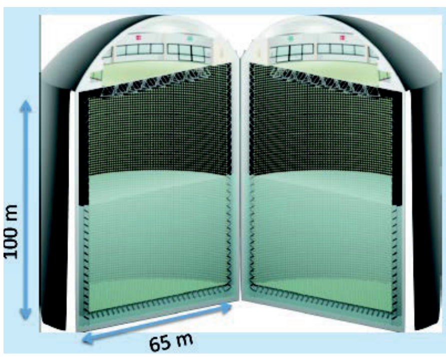
Accelerator-produced beams of neutrinos will enable experiments and applications that cannot be achieved using natural sources of neutrinos, such as from cosmic rays. Advanced experiments require a well-collimated very intense pulsed beam of neutrinos, and natural sources do not have such characteristics.

4. Interest in Discovering Neutrino CP Violation.

The discovery of neutrino oscillations was the subject of the 2015 Nobel Prize in physics. The next step is to discover and measure neutrino CP (charge parity) violation by seeking to observe a difference in the behaviour of neutrinos and anti-neutrinos. Further explanation of the significance and implications of neutrino CP violation is given in an Appendix to this proposal. If neutrino CP violation is discovered, this will contribute decisively to our understanding of the existence of matter in the universe, taking us beyond current physics.

5. Technical Challenges

The ESS Super Beam project presents several technical challenges. One is to work out the details of how to double the average power of what will already be the most powerful accelerator in the world, by adding more accelerator pulses. Another is how to use these extra beam pulses to produce a neutrino beam, third is how to measure the neutrino oscillations using a huge underground water-based Cherenkov-type neutrino detector that is to be installed 540 km north of Lund ca 1000 m deep in the Garpenberg mine, located in the south-eastern part of Dalarna county, Sweden. But our team of physicists and engineers is up to the challenge.



Garpenberg Mine Neutrino Detector. The detection of neutrinos in the Garpenberg mine will require a detector volume of one million cubic meters excavated to a depth of about 1000 m. To create such a huge cavern represents a significant technical challenge for modern mining technology. Water to fill this cavern will need to have a sight line of the order of 100 m and therefore must be maintained ultrapure using advanced and high capacity filtering techniques.

The detection of the faint light created when a neutrino interacts with an atomic nucleus in the water will require several hundred thousand highly sensitive light detectors mounted on the cavern walls. The monitoring of the neutrino beam generated at ESS will require even more sophisticated detectors to be developed and installed in the neutrino beam on the ESS site.

6. Other benefits of Super Beam project

The generation of neutrinos requires that the high-energy 2.84 ms long proton pulses be compressed to only 1.5 microseconds. To achieve this pulse compression, a special "compressor ring," consisting of a circular vacuum beam tube, 450 m in circumference and furnished with bending magnets, will be built and operated for the neutrino beam project. This will also be of use for materials research carried out using ESS neutrons. Such research requires the determination of the velocity of neutrons, which is done by measuring the flight-time of neutrons over a given distance. However, the 2.84 ms duration of a proton pulse does not provide a starting time of sufficient precision. Thus, the long neutron pulse created from the proton pulses will be *chopped* into much shorter pulses to obtain a sufficiently high time resolution. If, on the other hand, the proton pulses are *compressed* into much shorter pulses from the beginning, the resulting short neutron pulses will be of much greater brightness than when using the chopping technique. To achieve such very intense short neutron pulses is of great interest for a number of neutron science applications.

The underground megaton water Cherenkov detector will be an excellent detector, not only for accelerator-generated neutrinos but also for neutrinos generated by cosmic rays in the atmosphere, solar neutrinos and neutrinos from cosmic sources such as supernovae. Investigation of neutrinos from such sources will provide further data both about neutrinos themselves and about astrophysical phenomena.

Yet another important purpose of the detector will be to search for the possible decay of the proton, another holy grail of physics. Proton decay is a hypothetical form of radioactive decay in which the proton decays into lighter subatomic particles. The proton decay hypothesis was first formulated by Andrei Sakharov in 1967. There is currently no experimental evidence that proton decay occurs, yet the ESS Super Beam could possibly change that.

7. Project Under Way

The European Spallation Source (ESS) is well under construction and the linear accelerator project is progressing according to the plan of putting a first ESS beam on target in 2022. The main status points are:

- The facility is currently being built by a consortium of some 100 European research institutes and universities.

- The long accelerator tunnel has been finished and installation of the cryogenics and the ion source has started.

- The Accelerator Division is recruiting according to plan and is ready to install and commission the accelerator and proceed with its operation.

European Spallation Source, Lund, Sweden (rendering)

8. Projections for Neutrino Super Beam Upgrade

Major modifications required for the doubling of the power of the ESS proton beam via a higher repetition rate and higher beam energy have been identified as follows:

- Three new electrical substations along the radio frequency (RF) gallery.

- A third main electrical station alongside the existing ones.

- High voltage (HV) cable trenches and the pulling of additional HV cables from the main station to the new substations. New HV cables between the substations and the modulators in the RF gallery.

- Installation of 8 more cryomodules containing the accelerating cavities and the associated RF power stations to increase the beam energy to 2,5 GeV.

- Change of klystron collectors so that 60% more average power can be produced.

- Installation of additional capacitor chargers to allow faster pulsing of modulators.

- Installation of an H^- source beam funnel alongside the existing proton source.

9. The Financial Case

The estimated total cost of the infrastructure for the Neutrino Super Beam Project is € 1,3 billion, comprising € 0,6 billion for infrastructure costs at ESS and € 0,7 billion for the megaton neutrino detector located about 540 km away in Dalarna. Such an investment can only be achieved by an international agreement similar to that made between 10 European nations for the ESS base-line project.

The Neutrino Super Beam project is driven by a consortium which involves 15 research institutions in 11 European nations. This consortium is currently pursuing a Design Study of the project supported by the EU Horizon 2020 INFRADEV programme. It is also supported by the EU COST Association with means to cover travel and meetings costs. Investigation of the possibility to finance capital costs of the construction project can only be done once the current Design Study and the work on the subsequent Technical Design Report have been completed.

10. Interim Budget Secured:

- € 0,5 million from the European COST Association to cover the cost for travel, meetings and scientific visits for the Design Study, over a period of three years.

- € 3,0 million from the EU Horizon programme and € 1,7 million from the participating institutions to employ nine full-time post-docs and a number of part-time senior scientists over a period of four years to conduct the Design Study.

11. Financial requirement

We are currently in need of € 5,0 million to cover:

- The drilling of 20 test holes in the mine in Dalarna, the site of the large neutrino detector, in order to measure the pressure in the rock and its strength needed for the design work of the one million cubic meter detector cavern. The cost of drilling is € 0,1 million per hole, in total € 2,0 million, and the cost for the design work is € 0.6 million.

- The cost for the purchase of 5 large photomultipliers of different types for the large neutrino detector is € 0.1 million and the cost to test these light detectors is € 0,1 million.

- Design, construction and test work of a prototype neutrino detector that will be installed in the neutrino beam on the ESS site for **monitoring** of the neutrino flux in the beam and of the neutrino background. This detector, which will need to be tested in a CERN beam line, will consist of scintillators, optical fibres, small solid-state light-detectors and read-out electronics. This cost is € 1,3 million.

- Design, construction and test work of another prototype neutrino detector to be installed in the neutrino beam on the ESS site for the **measurement** of different neutrino cross-sections (=interaction probabilities). This detector, which will be tested in a CERN beam line, will consist of a water tank, surrounding photomultipliers and read-out electronics. This cost is € 0.9 million.

12. Request

The Neutrino Super Beam Project requires € 5.0 million to cover test drilling of holes, design and construction studies and of equipment, all as detailed above, in order to keep the project moving forward. We are seeking funding contributions from enlightened, forward-thinking companies who want to fortify their corporate responsibility profile by being a part of this exciting project. This is an opportunity to make a contribution to a significant project.

In recognition of this, your company will have access on a gratis basis to esteemed theoretical and experimental physicists and engineers to help solve a problem that might be perplexing your company, even non-physics problems. Physicists have a unique way of looking at problems, distilling them to their essence and always looking at the simplest core solution. Your company will also have a plate with its name on equipment of the Super Beam project, and recognition in our publicity and promotional materials. Your company will also be able to promote its contribution in its advertising and promotional material. Overall, a company can be gratified by supporting one of the most important scientific experiments on the planet.

Tord Ekelöf, Professor of Physics
ESSnuSB Scientific Leader
Uppsala University
tord.ekelof@physics.uu.se
+46 704 250 210

David Burman, JD
Director
Brahe Foundation
burmanda@mac.com
+46 760 074 410

Further technical details are available on request.

We are a team of 50 scientists and engineers waiting to consult for you. Here are our team leaders from 15 research institutions.

Appendix – CP Violation

For a long time, the neutrino was thought to be without mass similar to the massless photon, That the neutrino has no mass is even a basic assumption in the current general theory of elementary particles, called the Standard Model.

In 2015 Takaaki Kajita and Arthur B. McDonald were awarded the Nobel Prize in physics in 2015 for the discovery of neutrino oscillations, through which the neutrinos change into different types. Since such oscillations can be explained only if neutrinos have mass, this discovery contradicts the Standard Model. The next challenge is to discover and measure CP (charge parity) violation. The phenomenological description of neutrino oscillations contains six parameters that are by now all well measured experimentally, except one, which is the so-called CP violation angle. It is now important to measure this CP violation angle. If it is different from 0 degrees or 180 degrees, the violation of neutrino charge-parity symmetry (in short, neutrino CP violation) will have been discovered.

In particle physics, every type of particle has an associated antiparticle with the same mass but different quantum numbers. The Big Bang model states that the universe started from a concentration of energy in which virtual particle-antiparticle pairs were continuously created and annihilated. As the universe expanded, it cooled, which meant that matter and antimatter, in exactly equal quantities, took more persistent form. Gradually, however, antiparticles collided with particles and each such collision led to the annihilation of the particle with the antiparticle and the emission of two photons. This eventually caused the elimination of all antiparticles. The question is then how did it come that there still are particles, i.e., matter, present in the universe and not only photons, i.e., light? This is one of the greatest unsolved mysteries in modern physics and cosmology.

If an asymmetry in the behaviour of the neutrino and the antineutrino-asymmetry is observed and neutrino CP violation is thus discovered, this will contribute decisively to our understanding of the existence of matter in the universe, taking us into a realm beyond current physics.

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