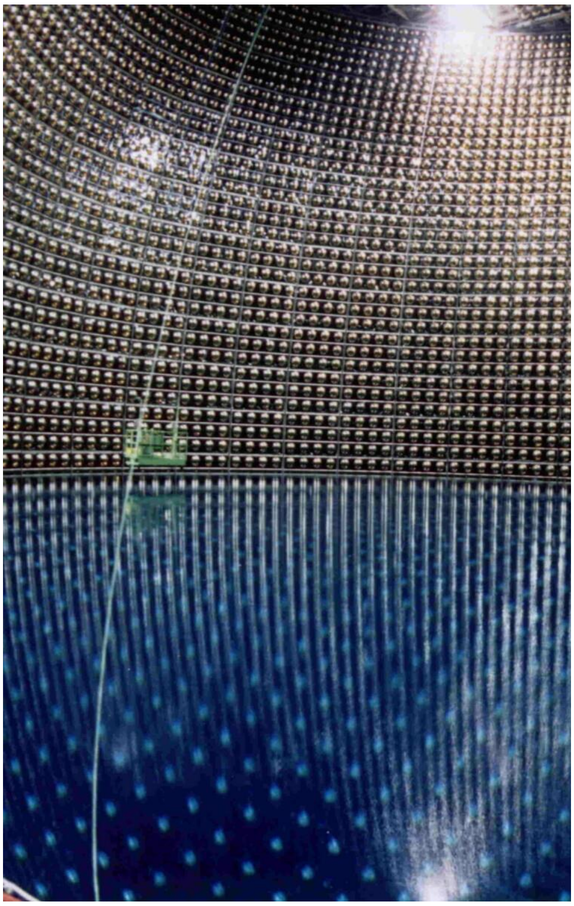
The original in Swedish language of the text below was published in the Swedish newspaper Ny Teknik (New Technology) on 6 April 2023.

Why is there matter in Universe? The researchers want to build particle detector 1,000 meters below ground level



We still have no explanation of why there is matter in the Universe

Researchers have been granted 3 million euro to draw up plans for a giant detector far below

ground level.

They want to send a neutrino beam from ESS in Lund, a beam that quickly expands and becomes kilometres wide on its way up through the country – the answer to the riddle of matter is to be sought with the "ghost particles".

Bill Burrau REPORTER

Jonas Askergren NEWS GRAPHIC ARTIST

ESS photographed from above in April 2022. Perry Nordeng/ESS

Outside Lund, the world's most powerful neutron source, the European Spallation Source (ESS), will soon be ready. Although the building is not finished, an international research group already wants to increase its power from 5 MW to 10 MW.

The ESS Neutrino Super Beam (ESSnuSB) project has recently received a second grant from the EU of 3 million euro. The goal is to answer a fundamental question about the universe: why does matter exist?

In order to find out the answer, the researchers want to send a particle beam from the ESS almost 400 kilometres towards a huge water-filled detector. The beam will expand and be kilometres wide already in the county of Småland. The detector, in turn, needs to be built 1,000 meters underground, in a mine shaft, and be filled with ca 500,000 tons of water and ca 90,000 very sensitive photo-detectors.

A gigantic project, which requires two large facilities far apart from each other, everything to get a view of one of the Universe's most elusive particles: the neutrino.

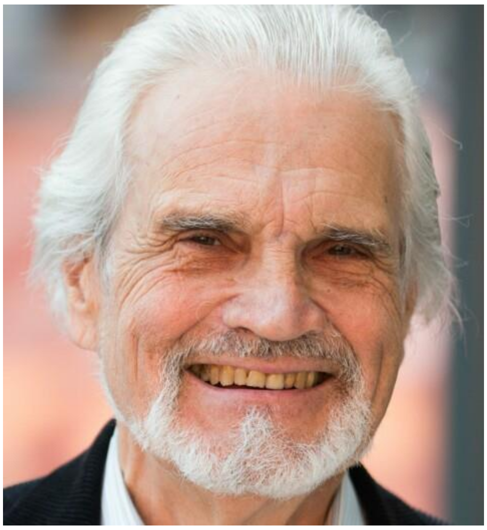
There should have been only radiation left after the Big Bang

The answer to why there is matter in the Universe will be sought in the difference in the behaviour between matter and antimatter. In short, every elementary particle has an antiparticle, a particle with the same mass but with, inter alia, opposite combination of charge (C) and parity (P), a quantum physics property.

If a particle and its antiparticle collide, they annihilate and the common mass is converted into radiation energy. Conversely, a particle can be created from radiation energy, then always together with an antiparticle.

- From the concentration of energy at the Big Bang, an enormous number of pairs of particles and antiparticles arose. The theory is that these then met and were annihilated after less than a fraction of a second - and only radiation would have been left. But all galaxies, stars, planets and ourselves are made of particles, at the same time as there are no antiparticles in the universe. We don't understand how this happened, says Tord Ekelöf who is professor of particle physics at Uppsala University.

Looking for asymmetry



Tord Ekelöf is professor of particle physics at Uppsala University. Private

The fundamental physics theories are based on the fact that there are certain symmetries in Nature. One of these is the CP symmetry which means that certain properties of a particle and its antiparticle are the same despite the differences in their combined Charge and Parity. In other words, a particle and its antiparticle should behave in the same way in some respects.

If the CP symmetry had been complete, all particles would have annihilated immediately after the Big Bang and there would have no matter or antimatter left. The result of the original annihilation of particles and antiparticles can be seen in the universe in the form of the cosmic background radiation.

However, observations show that there is an average of one proton per cubic meter in the universe, in addition the background radiation. There must therefore be a CP asymmetry – also called a CP violation.

- In 1962, CP violation was discovered in the quark sector. However, the measured CP violation of the quarks can only explain a mass density a billion times smaller than the one observed in the Universe. Our matter consists, in addition to quarks, of leptons, and there is the hypothesis that it is with the leptons that the effect of a CP asymmetry could be sufficient to explain the mass density we have in the universe, says Tord Ekelöf who is also the scientific leader of ESSnuSB.

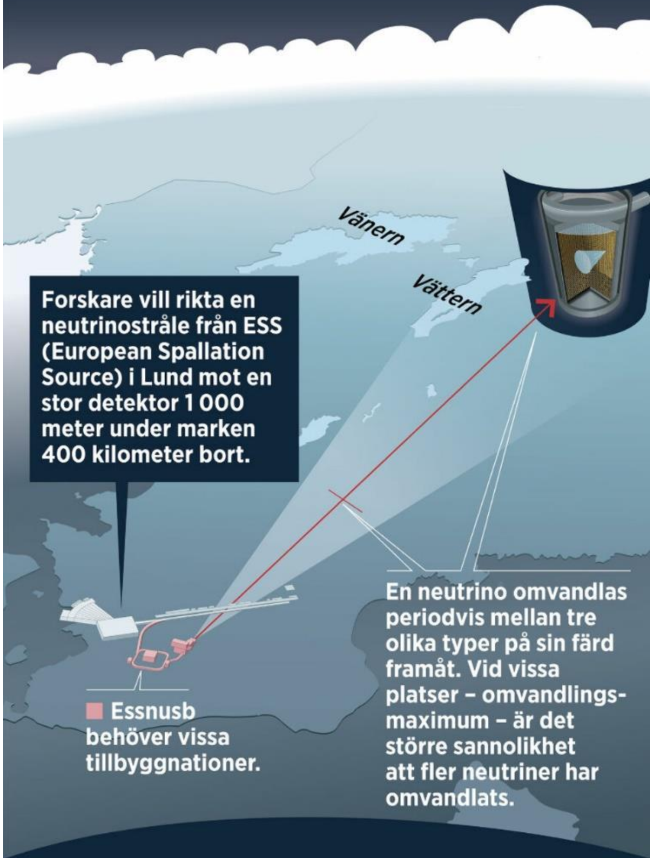
The scientists want to bombard the mine with ghost particles

The researchers want to look for a CP asymmetry with a particular lepton – the neutrino. The neutrino is also called the "ghost particle" as it so rarely interacts with matter.

- At ESS there will be an accelerator that will produces high-energy protons which will be made to hit a beam target. Pi-mesons are formed from the collision energy and decay immediately thereafter. A pi-meson can only decay in one way, namely into a muon and a muon-neutrino, says Tord Ekelöf.

There are good grounds for assuming that CP violations can be found in the neutrinos - in particular as these have properties that already are not described by the Standard Model. The Standard Model is the theory that is used today to describe the different elementary particles. According to it, neutrinos should be massless, and therefore could not exhibit a CP violation. However, in 1998 the discovery was made that neutrinos have mass, a discovery that was awarded the Nobel Prize in 2015.

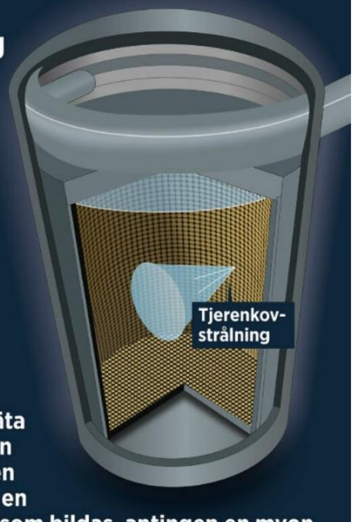
Neutriner ska fångas upp 400 km bort



Neutrinon är en nästintill masslös partikel som kommer i tre varianter – den oscillerar dessutom mellan dessa medan den rör sig framåt. Genom att undersöka oscillationen och jämföra andelen omvandlade partiklar med andelen omvandlande antipartiklar vill forskarna besvara en av universums mest fundamentala frågor – varför finns det massa?

Tjerenkovstrålning bildas av snabba partiklar

Neutriner interagerar väldigt sällan med materia, därför behöver en detektor vara väldigt stor. 1 000 meter under marken ska ett bergrum fyllas med 500 000 ton vatten och 90 000 fotodetektorer.



Detektorerna ska mäta Tjerenkovstrålning. När en neutrino kolliderar med en syreatom i vattnet bildas en laddad lepton. Leptonen som bildas, antingen en myon eller en elektron, kommer att röra sig snabbare än ljusets hastighet i vatten. Detta ger i sin tur upphov till ett blått sken – Tjerenkovstrålning – som kan mätas.

Fakta: Bill Burrau Grafik: Jonas Askergren

There are three known types of neutrinos: electron, muon and tau neutrinos. Observations have shown that these transform into each other back and forth in an oscillating manner – something that can only happen if they have mass. A neutrino will thus be transformed periodically between the three varieties during its journey to the neutrino detector.

- The neutrino beam that will be created in Lund only consists of muon neutrinos. Some of the neutrinos in the beam will collide with atomic nuclei in the underground and very large neutrino detector. From these collisions we can identify and distinguish the electron neutrinos that arise from the conversion of muon neutrinos on the way from Lund to the detector, says Tord Ekelöf.

Neutrino interactions happen very rarely and to increase the chances the detector needs to be very big. The plan is to have ca half a million cubic meters of water in two big underground caves with roughly 90,000 photo-detectors mounted on the inner walls of the caverns. The detector needs to be 1,000 meters below ground for the measurements not to be disturbed by the cosmic radiation.

The creation and installation of such a detector is facilitated if it can take place in the vicinity of an active mine. The Zinkgruvan mine near Örebro is located at the right distance from ESS and Lund and thus constitutes an interesting place for the researchers.

Ten years of measurements – five with neutrinos and five with antineutrinos

When a neutrino hits an oxygen nucleus in a water molecule in the cave, it is converted into a charged lepton. A muon neutrino is converted into a muon and an electron neutrino is converted into an electron. The researchers want to shoot muon neutrinos from the ESS for five years to collect data on the transformation.

The newly formed lepton will move faster than the speed of light in water, giving rise to Cherenkov light, which is to be measured using very sensitive photo-detectors. One can distinguish between muons and electrons by analysing the distribution of the Cherenkov light. By measuring the number of observed electron-neutrinos and muon neutrinos, one will see how large a percentage of the muon neutrinos that has been converted.

The trick is then to redo the five-year experiment, but instead of sending a beam of muon neutrinos from ESS send a beam of its antiparticle – muon anti-neutrinos.

- If there is no CP violation, the fraction of muon neutrinos that are converted to electron neutrinos should be the same as the fraction of muon antineutrinos that are converted to electron antineutrinos. We will look for a small difference between these two proportions, which would be a sign of CP violation. If the difference is large enough, it can explain why there is matter in the amount that is observed in the universe, says Tord Ekelöf.

The transformation of a neutrino between the different types follows a sinusoidal curve during its progress in the beam between Lund and the neutrino detector. In certain places, the probability to find electron neutrinos is at maximum. To increase the chances of detecting electron neutrinos, ESSnuSP plans to place its detector at a conversion maximum. Similar projects in Japan (Super-Kamiokande) and the United States (DUNE) plan to install their detectors at the first transformation maximum according to Tord Ekelöf. ESSnuSB's neutrino detector will instead of be installed at the second conversion maximum.


Neutrinodetektorer i världen
Dune är en planerad detektor som byggs i USA.
KM3Net ska använda vattnet i Medelhavet för att mäta partiklarna.
Baikal-GVD mäter hur neutriner interagerar med vattnet i Bajkalsjön.
Ice Cube använder Antarktis is för att detektera neutrinointeraktioner.
Super-Kamiokande är en detektor i en stor gruva i Japan.
Foto: Super-Kamiokande

- For ESSnuSB, the first maximum is in southern Småland and the second maximum three times further away, near the Zinkgruvan mine. The reason we want to measure at the second maximum is that the CP violation signal can be expected to be almost three times stronger there, something that was only realized in 2012 based on of results of new measurements of neutrino oscillations that were published at that time, he says.

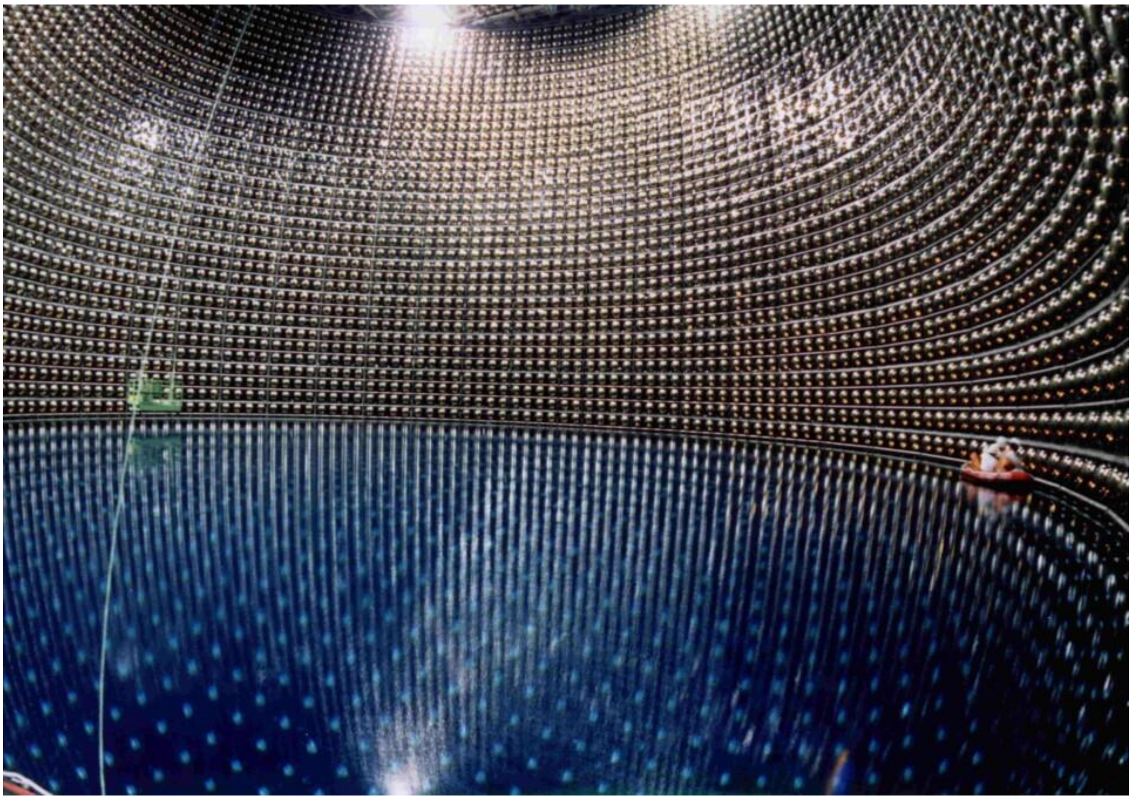
The neutrino beam will expand and be kilometres wide already at first the oscillation maximum. As the detector is smaller than the beam width, the proportion of particles that are detected is reduced in proportion to the inverse square of the distance from the source, ESS. Since the distance to the detector at the second maximum is three times longer, the intensity of the neutrino beam need to be nine times higher.

ESS's powerful accelerator can create a sufficiently intense neutrino beam to enable measurements at the second oscillation maximum. Tord Ekelöf estimates that one should be able to create at least 10^{14}, 100 trillion, neutrinos per second at ESS. Of these, however, only a few neutrinos per week will be detected.

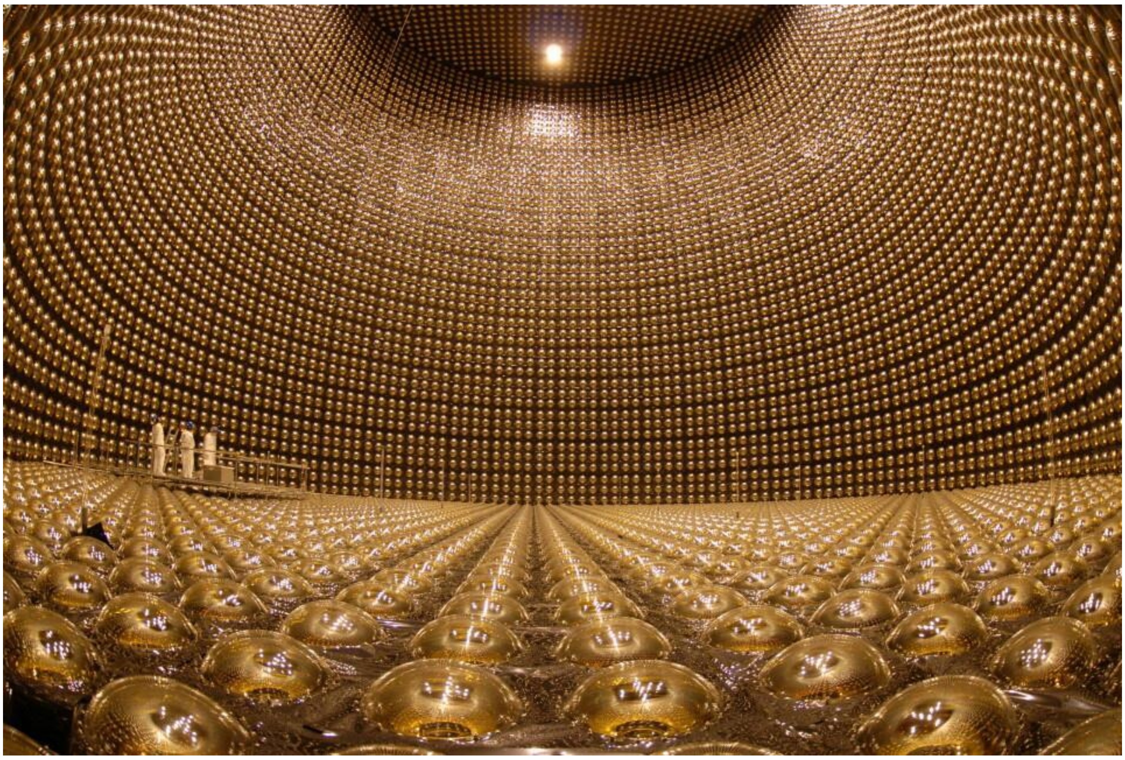
The ESS beam power needs to be doubled

ESSnuSB's second grant of 3 million euros will be used to develop details about the required equipment and instrument in the coming years. When everything is ready in December 2026, the scientists have given themselves two more years to collect investment funds from the various countries in Europe, the estimated need is around 1.7 billion euros. The construction of the detector is expected to then take seven years. After this, the planned period of ten years of measurements will begin.

One of the photo-detectors at the Super-Kamiokande. Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo



Super-Kamiokande in Japan being filled with water in 1996.Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo



The interior of Super-Kamiokande without water. Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

An important part of the neutrino project is to double the power of the ESS accelerator from 5 MW to 10 MW. In this way 5 MW can still be used to create spallation neutrons for materials research according to the original plans for the ESS, and 5 MW to create the neutrino beam.

- You might think that it sounds very optimistic that we shall be able to, without further ado, double the power of the world's most powerful accelerator. But the ESS accelerator delivers 14 pulses per second, each of which is only 3 milliseconds long, so 70 milliseconds pass between these pulses. We can add 14 more pulses such that there will be only 35 milliseconds between pulses. For this more radio frequency power and more cooling for the accelerating cavities will need to be added. But these additions fit within the margins of the ESS as it already is designed and can be obtained for a relatively limited extra cost, says Tord Ekelöf.