Hunting for Particles Underground

Neutrinos are particles with seemingly magical powers: the different types are able to transform into one another, and thus have a mass. This discovery earned two scientists the 2015 Nobel Prize for Physics. A quarter of a century ago, these ghostly particles also attracted the attention of researchers at the **Max Planck Institute for Nuclear Physics** in Heidelberg for the first time. While conducting their Gallex experiment to hunt for them, they looked deep into the furnace of the Sun.

TEXT **HELMUT HORNUNG**

We can't see them, we can't feel them, yet they're everywhere. They penetrate everything – stars and planets, lead walls measuring light-years across, and even our own bodies. More than 66 billion of them shoot through the nail of your index finger every second. Neutrinos are the most common particles in the universe after photons, or light particles, yet their research history is relatively young.

In a letter written on December 4, 1930, Wolfgang Pauli mentioned such a particle for the first time, calling it a neutron. The Austrian physicist postulated the particle to explain the energetic conditions in the radioactive beta decay of an atomic nucleus. Enrico Fermi, an Italian, studied it in depth and gave the tiny theoretical particle the name "neutrino". Finally, in 1956, Clyde L. Cowan and Frederick Reines at the Los Alamos National Laboratory in the US succeeded in detecting this "mini neutron." The project to search for the neutrino was aptly called "Poltergeist."

Owing to its extremely weak interaction with matter, the fleeting phantom was very difficult to detect. This spurred the physicists on all the more to investigate it in greater detail in the years that followed. So the hunt continued, and in early summer of 1990, European scientists set a special trap for the ghostly particle from the interior of the Sun. To do this, they went underground.

In the spotlight: The media showed a great deal of interest in the results obtained by the neutrino hunters in the 1990s. Here, Gallex spokesperson Till Kirsten from the Max Planck Institute for Nuclear Physics at a press conference.

The Gran Sasso tunnel is a good 10 kilometers long. The A24 *autostrada* that runs through it links the cities of Teramo and L'Aquila as it crosses the Abruzzo region of Italy. After 6.3 kilometers, an exit leads off to a laboratory. Above its halls are 1,400 meters of rock, which forms a natural barrier against cosmic radiation and thus minimizes the "contamination effect" in the – extremely intricate – measurements.

The trap consisted mainly of 30.3 tons of gallium – half of the annual global production at the time. The gallium was delivered in six-packs of containers holding 1,200 liters of gallium chloride solution each. The liquid then had to undergo a 20-hour process to purify it of contaminants created by natural cosmic radiation. Only then was the gallium chloride put into one of two 30-cubic-meter tanks and dissolved in hydrochloric acid.

The tanks were made of corrosion-resistant material, glass-fiber reinforced polyester coated on the inside with polyvinylidene fluoride. This material contained extremely small amounts of natural radioactive substances such as radium, thorium or uranium. Only one tank was used for measurements at any one time, with the other kept in reserve as a precaution.

So how did they go about finding the neutrino? One of the researchers involved referred to it back then as a "special challenge for chemistry" – a slight understatement, which is why the media repeatedly reported that the whole project was more difficult than the proverbial search for a needle in a haystack.

The numbers speak for themselves: there were some one quintillion (10^{30}) atoms floating around in one Gallex tank. The scientists set a measurement period of 20 days. During this radiation period, the solar neutrinos were expected to score an average of ten hits – that is, collide with ten (!) gallium atoms and transmute them into germanium. In a nutshell: a hint of radioactive, gaseous and therefore extremely volatile germanium chloride was formed in the liquid gallium chloride.

At the end of a measurement period, these miniscule traces of germanium chloride were driven out of the tank using liquid nitrogen and, after a complex treatment process, were detected by

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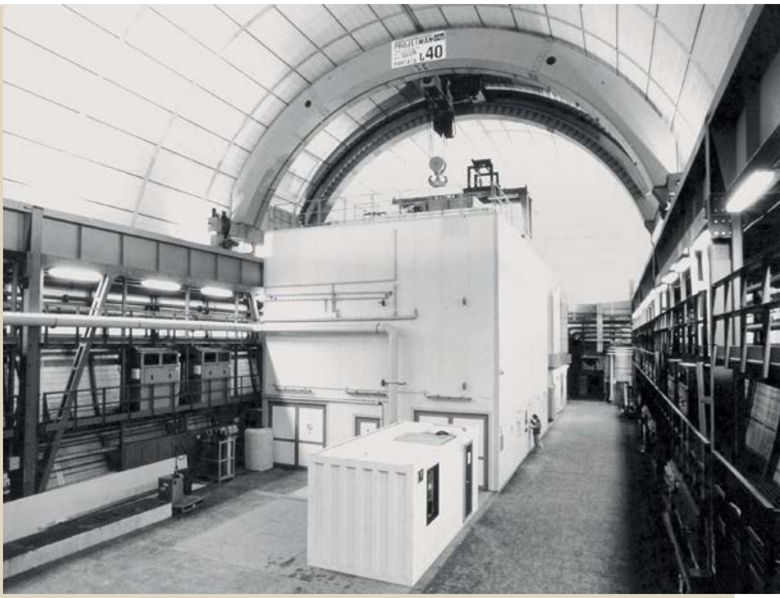

In the depths: In the Gran Sasso subterranean laboratory under 1,400 meters of rock, researchers gazed into the heart of the Sun. The Gallex experiment registered neutrinos generated by the stellar fusion reactor.

means of their radioactivity. The scientists then used the number of germanium atoms detected in this way to draw conclusions about the flow of neutrinos from the Sun.

The unusual location of the Gallex experiment deep below the rocks paid off. The researchers succeeded in reducing the germanium production resulting from the natural cosmic background radiation to a mere two percent of the neutrino-induced signal. In addition, the counting room was also surrounded by a Faraday cage that kept out the stray electric radiation coming from the outside.

The neutrinos that got caught up in the tank originated from the center of the Sun, where there is a gigantic fusion reactor at work converting hydrogen to helium at a temperature of well over 15 million degrees Celsius and a pressure of 200 billion bar.

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» With their sophisticated trap for the fleeting particles – a tank filled with thirty tons of liquid gallium – the researchers in the Italian mountains have received unambiguous neutrino signals.«

During this proton-proton reaction, as the process is called, two hydrogen nuclei (protons) first fuse to form a deuterium nucleus, releasing a positron (a positively charged electron) and an electron neutrino as they do so. In a second step, the deuterium nucleus fuses with a further proton to create a helium nucleus (^{3}He) and simultaneously emits a gamma quantum. In the final step, two ^{3}He nuclei fuse to form ^{4}He and release two protons.

During the proton-proton reaction, the Sun uses hydrogen to generate not only considerable amounts of helium, but also an inconceivable number of so-called pp neutrinos. These witnesses to the stellar fire leave the interior of the Sun unhindered and reach Earth a good eight minutes later. They account for roughly 90 percent of all solar neutrinos and, at 420 kiloelectron volts, have quite a low maximum energy. But Gallex was sensitive to this type of neutrino. The scientists eagerly awaited the result, having run into a dilemma in the years before the Gran Sasso experiment. They were racking their brains over the mystery surrounding the neutrino.

In the early 1970s, Raymond Davis was the first to detect solar neutrinos using a tank full of perchloroethylene in the Homestake gold mine in South Dakota. The problem was that there was only a third as many of them as the standard solar model predicted. The Japanese Kamiokande detector likewise found this discrepancy. However, the two detectors were sensitive to beryllium-7 and boron-8 neutrinos, which were thought to arise from a side chain of nuclear fusion. So was the theoretical scenario in the core of our Sun wrong?

Gallex entered the scene at just the right time, because the experiment was intended to capture the above-described, much lower-energy pp neutrinos for the first time. The result was published roughly a year after the facility had gone into operation: "First glimpse into the furnace of the Sun" was the title of a press release issued by the Max Planck Society on June 2, 1992. It reported that Gallex had tracked down neutrinos compatible with the predicted number. Till Kirsten from the Max Planck Institute for Nuclear Physics in Heidelberg, who headed the European Gallex collaboration, said, "The foundations of our explanation of nature behave in such a normal way that some sensation-seeking observers may be disappointed at this time."

From the very beginning of proposal writing and project planning, Gallex defined two major motivations. One was the definite detection of solar pp neutrinos, and the other was the search for neutrino mass, reflected in reduced electron-neutrino fluxes due to neutrino flavor oscillations between electron, muon, and tau neutrinos.

The first data set released in 1992 proved the first item, but the statistical significance concerning the second one was far too low for a positive claim. Ensuring this option required patient solar neutrino data collection for many more years and an elaborate calibration with a man-made megacurie low-energy neutrino source. In 1997, the significance of a neutrino flux deficit due to neutrino oscillations had reached more than 99.9 percent.

In 2001, researchers working with Canadian physicist Arthur B. McDonald published their measurement results, which the team working with Japanese physicist Takaaki Kajita confirmed. As the electron neutrinos travel the 150 million kilometers from the Sun to Earth, they slip into the role of their relatives, instantly changing into tau and muon neutrinos, to which traps like Gallex were blind. For them to convert, they must have a mass, albeit a very low one. And that's how the two scientists finally managed to detect the ghostly particles – and walk away with the 2015 Nobel Prize for Physics.

The work in Italy's Abruzzo region goes on. One experiment there, known as Borexino, has also been on the trail of solar neutrinos for the last couple of years. Adjacent to it are the traps that are designed to capture particles of the enigmatic dark matter that makes up one-fourth of the cosmos and whose nature is still completely unknown. The underground researchers apparently specialize in solving the most difficult mysteries in the universe.

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