The Majorana Neutrino and the Universe

Our Universe is the result of an initial explosion often referred to as the "Big Bang". The original matter, which was concentrated at a single point in spacetime, expanded to form the origin of the structures that we see today, including galaxies, stars, and planets. Today, the Universe as we know it, is primarily made out of matter, and not of antimatter. Why and when antimatter disappeared and matter became dominant—making the existence of stars and planets as we know them possible—is not known. The experimental observation of neutrinoless double-beta decay and the resulting confirmation of the Majorana nature of the neutrino would allow us to explain in part the prevalence of matter over antimatter in the Universe, through a process known as leptogenesis, and the creation of the large-scale structures in the Universe that we observe today.

Ettore Majorana: The Story of an Idea

The theoretical ideas behind CUORE's research are over 80 years old. In the 1930s, Ettore Majorana was a member of Enrico Fermi's research group in Rome (known as the "Via Panisperna boys", from the name of the street where Fermi's research lab was located). In 1937, Majorana published his famous paper, "A Symmetric Theory of Electrons and Positrons", proposing that neutrinos and antineutrinos could in fact be the same particle. In 1939, Wendell Furry observed that Majorana's model could give rise to neutrinoless double-beta decay, building off the theory of double-beta decay proposed four years earlier by Maria Goeppert-Mayer. The interest of the scientific community in this process has grown over the years, and today many experiments worldwide are trying to prove—or disprove—Majorana's hypothesis.

30 Years of Measurements at LNGS

CUORE is a culmination of multiple previous experiments searching for neutrinoless double-beta decay in the Gran Sasso National Laboratory. Thanks to skills developed over the years, starting from the pioneering work of Ettore Fiorini with single crystals of a few grams, the first cryogenic bolometer towers were built, followed by Cuoricino (2003-2008), CUORE-0 (2013-2015), and finally CUORE (beginning in 2017), the world's first ton-scale bolometer experiment.

Collaboration

CUORE is a collaboration of over 150 scientists mainly from institutions in Italy and the United States. CUORE is supported by: Istituto Nazionale di Fisica Nucleare (INFN), US Department of Energy (DOE) Office of Science, National Science Foundation (NSF), Alfred P. Sloan Foundation, University of Wisconsin Foundation, Yale University and National Energy Research Scientific Computing Center (NERSC).

Images: Yury Suvorov and Volker Steger

INFN
LABORATORI NAZIONALI DEL GRAN SASSO

CUORE

A Search for Neutrinoless Double-Beta Decay

Neutrinos are extremely light, electrically neutral, and quite abundant in the Universe. Yet despite their abundance, they almost always pass through matter completely unperturbed and undetected. This makes them very difficult to study, requiring large and complicated experiments at dedicated facilities around the world.

Experiments have shown that more than one family of neutrinos exists, that neutrinos from different families can change into one another, and that neutrinos have a very small—but nonzero—mass. Yet despite the incredible progresses of recent decades, we have not yet been able to measure the masses of the three known families of neutrinos, nor do we know which neutrino is the lightest. The relationship between neutrinos and their antiparticles is also mysterious: are neutrinos and antineutrinos exactly the same, as predicted by Ettore Majorana, or different, like every other known fundamental particle of matter?

Physicists have postulated a process that, if observed, could answer some of these questions: neutrinoless double-beta decay. In neutrinoless double-beta decay, a nucleus would decay emitting only the two electrons and no neutrinos, thus violating the rules of the Standard Model of Particle Physics. This process, proposed in 1939 but not yet observed, could open the door to theoretical physics models seeking to explain why there is more matter than antimatter in the Universe.

In recent decades, several experiments have searched for neutrinoless double-beta decay using increasingly advanced technologies. Detectors must have a very large mass, with superb energy resolution and exquisitely low background radiation, in order to see a signal. If observed, the experimental signature of the decay would be quite clear but very rare; we expect to see only a few decays in 5-10 years of data-taking with a tonne-scale detector!

The Detector

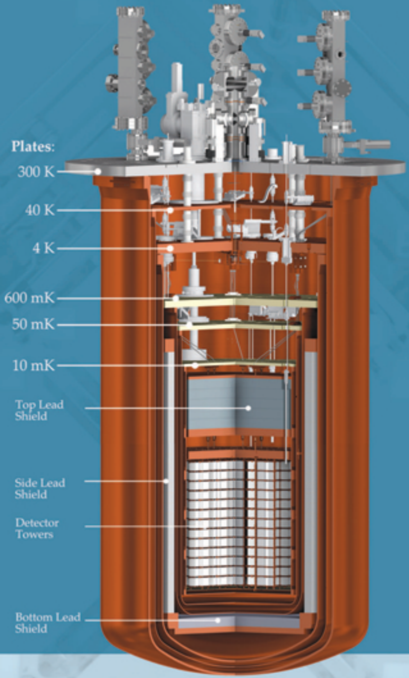
CUORE uses 988 ultra-cold tellurium dioxide (TeO_2) crystals arranged into 19 towers. The crystals contain the candidate neutrinoless double-beta decay isotope tellurium-130 (^{130}Te).

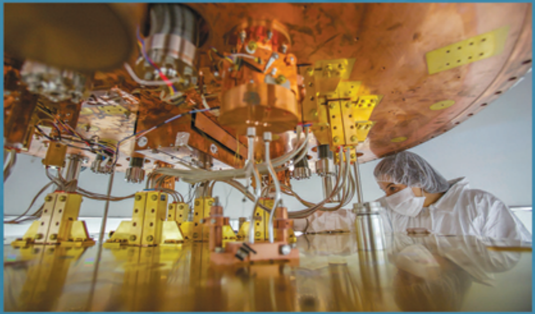
Tellurium is a good choice for this kind of detectors. The isotope ^{130}Te can undergo neutrinoless double-beta decay because it is known to undergo two-neutrino double-beta decay, which is the primary requirement. The isotope also comprises over a third of natural tellurium, so we can avoid difficult and expensive isotopic enrichment. And out of the isotopes that undergo double-beta decay, ^{130}Te decays at a relatively high energy, which makes it easier to pick out the decays over background signals. The tellurium dioxide crystals have low intrinsic radioactivity and are mechanically stable, so the detectors can be operated for years.

Every time a tellurium nucleus decays or a particle interacts in the crystal, it releases a minute amount of energy (less than a few MeV), raising the temperature of the crystal slightly. This rise in temperature is then converted into an electrical signal using temperature-dependent resistors (thermistors). For this temperature rise to be measurable, the baseline temperature of the crystals must be very low.

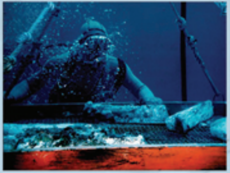
For these reasons, the CUORE detector, with a total mass of 742 kg, and several tonnes of shielding, is enclosed in a dedicated cryostat, capable of cooling down such a mass to a few thousandths of a degree above absolute zero (-273.14 °C). To reach this extremely low temperature, the cryostat is cooled in two stages. The first stage cools the detectors to a few degrees above absolute zero using pulse tube cryocoolers. The second stage cools the detectors further using the unique properties of a mixture of the helium isotopes ^{3}He and ^{4}He, which allows the experiment to reach the desired temperature.

Nested copper vessels inside the cryostat preserve a vacuum and temperature gradient and, together with an inner lead shield, prevent external radioactivity from interfering with the measurement. Outside the cryostat there is a further layer of lead to stop gamma rays from interacting in the detector, and the lead is surrounded by borated polyethylene to stop neutrons. The Gran Sasso mountain itself forms the final layer of shielding against cosmic rays.





Roman Lead



The lead used in the CUORE inner shielding is from a ship that sunk between 80 and 50 b.C. off the coast of Sardinia. About a thousand ingots, weighing 33 kg each, were extracted in a campaign of diving expeditions funded by INFN in collaboration with the Italian archaeological heritage ministry. Of the ingots recovered, 270 are currently being used for physics experiments. Each of the lead ingots has a unique stamp that records some of its manufacturing history, including the name of the Roman family who cast it. These inscriptions are priceless archeological sources and are being studied at the National Archaeological Museum in Cagliari, in southern Sardinia.

Lead naturally contains the radioactive isotope lead-210 (^{210}Pb) as a result of natural contamination from uranium in the Earth's crust. The half-life of ^{210}Pb is 22 years, so as the lead ages, the ^{210}Pb decays away, leaving the lead less radioactive as it gets older. Because of this, the oldest pieces of lead are the best for low-background experiments. In each kilogram of naturally occurring modern lead, there can be up to a few hundred radioactive decays per second. This activity has completely decayed away in the Roman lead used in CUORE; when Roman metallurgists purified this lead in order to extract the residual silver, they also removed the natural contaminants so well that it compares to the best prepared modern lead samples. Using this lead gives CUORE a unique opportunity to create an extremely radiopure environment.

Protecting the Experiment from Humans

As it is visible in the photographs, researchers wear special suits while working on the experiment to prevent any contamination. The purpose of this dressing procedure is not to protect humans from the experiment, but instead to protect the experiment from humans. In fact, the CUORE experiment is so sensitive that even a single drop of human sweat can seriously contaminate the experiment, spoiling its sensitivity, especially when the detectors are exposed while they are installed in the cryostat (pictured above) or during technical checks of the detector.

The Coldest Cubic Meter in the Universe

Though the temperature reached by the CUORE detector is not the coldest temperature ever recorded, the experiment holds its own record: the CUORE experimental volume is the coldest cubic meter in the known Universe. In fact there is no other structure in nature or built by humans that is simultaneously so large and so cold. Even the temperature of interstellar space is about 2.7 degrees hotter than the inner heart of the CUORE cryostat.