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Istituto Nazionale di Fisica Nucleare

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FROM DETECTORS TO DARK MATTER: EUROPE REWARDS RESEARCH WITH PARTICLE ACCELERATORS

Interview with Lorenzo Bianchini, researcher of the INFN Pisa division, and Andrea Celentano, researcher of the INFN Genoa division, respectively winners in 2020 of an ERC Consolidator Grant and an ERC Starting Grant, for a total funding of over three million euros

ASYMOW and POKER are the names of the two INFN projects awarded in 2020 by the European Research Council (ERC) for their innovative character and for the merit of their applicants: Lorenzo Bianchini, a researcher at the INFN Pisa division, and Andrea Celentano, a researcher at the INFN Genoa division. The goal of the two projects is to develop innovative techniques for analysing data obtained from LHC accelerator collisions and to study light dark matter.
The idea on which the ERC Grants are based is to finance innovative research projects following a bottom-up approach, involving researchers of any nationality and age, who are at the start of their careers or are intending to pursue their research paths by developing unconventional methods. The ERC Consolidator Grant, in particular, is awarded to excellent researchers with at least seven and up to twelve years of post-doctorate experience. In the 2020 funding round, Lorenzo Bianchini was awarded 1,683,750 euros for the project ASYMOW power to the LHC data - an ASYmptotically MOdel-independent measurement of the W boson mass. The project's main goal is to develop a new methodology for analysing data and calibration techniques for the CMS detector, one of the four big experiments of CERN's LHC that, alongside ATLAS, enabled the discovery of the Higgs boson.
Devised to incentivise the initial phase of excellent researchers' careers, and intended for researchers with 2-7 years of post-doc experience, the ERC Starting Grant 2020 awarded Andrea Celentano almost 1.5 million euros in funding for the POKER project (POsitron resonant annihilation into darK mattER). This project is dedicated to researching a particular type of dark matter: light dark matter.
We asked Lorenzo Bianchini and Andrea Celentano to explain the investment strategy for the grant that was awarded to them, as well as the aims and development prospects for their research projects.

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Lorenzo Bianchini can you explain your project and its objectives? In your opinion, why did the ERC consider it promising?

[LB] The ASYMOW project aims to provide a precise measurement of the W boson's mass, a quantity that has an essential role in particle physics. The measurement of the W mass is not new in itself: the first determination, with a precision of approximately 1 part per 20 coincided with the discovery of the W boson, in 1983 (a discovery recognized the following year with the award of the Nobel Prize to Carlo Rubbia and Simon van Der Meer, ed.). Today, the W mass is known with a precision of approximately 1.5 parts per 10,000, but we'd like to push that even further. Even reducing the experimental error by just half would be an ambitious result with far-reaching consequences. It would enable, for example, a more significant comparison with the prediction provided by the Standard Model regarding the W mass - a prediction that is, now, more precise than the measurement and, actually, in slight contrast with the latter. It is just this intrinsic capacity to test theory that underlies the great interest the W mass has always inspired in collider physics. Today, in any case, this research programme seems to have hit the brick wall of systematic uncertainties, despite the LHC accelerator having an enormous potential in this field. In this regard, ASYMOW proposes a new approach that leverages the great statistical power of the LHC to round the wall of systematic modelling uncertainties. Analysing an enormous mass of events will require a huge experimental effort to understand, in depth, the detector and know how to interpret its data. I think that the ambition of joining the small (experimental uncertainty) with the big (number of data) was seen as an unprecedented challenge for this type of measuring and capable of opening future opportunities.

The CMS experiment, like all LHC experiments, will undergo significant upgrades in the coming years to address implementations planned for the accelerator. How does ASYMOW fit in with this innovation path for the LHC?

[LB] The LHC detector upgrades will enable the latter to withstand the high-luminosity collision of HL-LHC. While opportunities for new measurements, not yet possible today, will arise thanks to this upgrade work, interest in other measurements risks to extinguish because, for example, limited by theoretical systematic uncertainties or by the detector. The ASYMOW paradigm is the one to succeed in harnessing the statistical power of data, learning from the latter what the theoretical models, or the detector simulations, can't predict precisely enough. If this ambition is satisfied, we will have one more demonstration of the importance for LHC to continue its data collection process for a long time.

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What difficulties do you expect to have to find in the five years of the project, in terms of technological limitations, obstacles in the research process, and your team's motivation?
[LB] The measurement of the W mass in hadron colliders is historically a difficult one, precisely because of the very high degree of precision that it requires in many respects. In desiring to analyse many more data than in similar measurements in the past, and, moreover, with a new method, ASYMOW adds additional challenges. Recent technological developments in many areas of interest for the project (I'm thinking, for example, of recent and more precise theoretical calculations, new and more usable forms of computational acceleration, analysis software developed by big High-Tech companies, etc...) provide opportunities yet unexplored that I'll have to carefully weigh up. Regarding the scientific goals, the level of experimental challenge is such that I don't expect to see immediate results. Instead, we will have put the pieces of this puzzle together with patience along the whole arc of the project. It will, therefore, be a challenge to develop and propose a rich and complex research path to the team of people who will work with me, a path that offers opportunities for individual growth without losing sight of the ultimate objective. In this way, I believe that team work will be fundamental at all levels: between the members of the team, between the team and the local and national research groups (I'm thinking, for example, of the CMS Italia community), and, finally, with the CMS collaboration and other LHC experiments.

What results do you expect at the end of five years?
[LB] The main goal I expect to reach at the end of the project is that of having published a measurement of the W mass with a precision of at least 10 MeV, a factor of 2 more precise than the best single experiment today. Such a measurement would have a significant experimental impact, including the ability to throw light on the current tension with the Standard Model prediction. But it's not just that: I would like to have made progress in developing new data analysis and detector calibration techniques that could be used in the future, by the CMS experiment, or even by experiments with next generation of colliders. For me, it would be a source of pride if the project managed to inspire interest in students and attract them to high energy physics. Abundant opportunities are expected for this research sector, as reiterated by the latest update of the European Strategy for Particle Physics. The resources that the ERC provides are consistent and make it possible to reach the so-called, "high risk, high gain" objectives. I'd like, beyond the scientific gain, for ASYMOW to give young researchers the opportunity to grow and consolidate their experience as scientists, to ensure that the immense know-how that they'll be able to cultivate during the implementation of the project remains and gives its results.

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Andrea Celentano, what path led you to dedicate yourself to dark matter research? And what do you mean by light dark matter?
[AC] The "light dark matter" hypothesis is a new, alternative explanation for the nature of "dark matter", which complements the traditional one linked to WIMP. According to this hypothesis, dark matter is composed of new light particles, of a mass similar to or less than that of the proton, which interact with ordinary matter via a new force present in nature, with characteristics similar to the electromagnetic force, but of much reduced intensity. Precisely because of the small mass, the traditional measuring techniques used for WIMP research have a reduced sensitivity to this new hypothesis, which can, instead, be effectively investigated using experiments performed in particle accelerators, using medium-energy, intense beams, in particular in a fixed-target configuration.
I began working on light dark matter research within the HPS (Heavy Photon Search) experiment at the Jefferson Laboratory, in the US, during the last year of my doctoral thesis, i.e., practically at the dawn of this recently developed research field. Thus, I've had the chance to actively participate in its development and in the growth of the community both being a co-proponent for new experiments, such as BDX (Beam Dump eXperiment) at the Jefferson Laboratory, and with ideas for new research, such as that underlying POKER.

Can you explain your project and its premises? In your opinion, why did the ERC consider it promising?
[AC] Currently, research into light dark matter with particle beams on a thick target is based on two experimental techniques. In the beam-dump experiments, the recoil of light dark matter produced in the target on a detector placed beyond the latter is measured, while in the missing-energy experiments, the detector is the target itself, which measures the energy deposited inside of it by every particle of the colliding beam. The production of any dark matter particles, which would bring with it a big primary energy fraction, would be observed as a difference between the measured energy and the nominal energy of the beam. POKER will study the feasibility of a new approach to face this physics problem, using an energy beam of positrons on an active thick target, to exploit the production of light dark matter by means of electron-positron resonant annihilation.
The beam of positrons is the key to POKER. The innovative idea for its use in a missing-energy type setup rose from contact with the community of the INFN Frascati National Laboratories, where the theoretical basis of resonant annihilation was developed and where PADME (Positron Annihilation into Dark Matter Experiment), an experiment searching for light dark matter with a positron beam on a thin target, was established.
Using positrons, POKER will be able to exploit the strengths of both approaches described above:

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the great intensity of the signal typical of the missing-energy configuration and the intrinsic ability to eliminate background events, which characterises the beam-dump approach. In my opinion, this is the great strength of the project, which helped us to obtain the prestigious ERC funding.

How will you use the funding you obtained? Are you sharing the project with a research team?
[AC] The goal of POKER is to carry out a demonstration measurement, exploiting the positron beam of 100 GeV available at the H4 line of CERN, with which the NA64 experiment is currently performing a missing-energy measurement with an electron beam with similar characteristics.
While I imagine using part of the NA64 experimental infrastructure for the measurement, such as, for example, the diagnostic and monitoring part of the beam, I imagine using a significant part of the funds obtained to create an active, ad-hoc target for the measurement: a high-resolution electromagnetic calorimeter consisting of lead tungstate crystals. All the costs linked to this activity - the purchase of the crystals, of the related photosensors, and of the reading electronics, as well as the construction of the same and its integration in the experimental facility - are integral parts of the project.
In addition, using the ERC resources, I'll be able to build a research team with which to move POKER forward, opening several post-doc positions during the five years envisaged for the project.

What results do you expect at the end of the five years window?
[AC] I think POKER will be considered a success if, in five years, my research team and I will have been able to complete the first exploratory measurement at CERN, thus demonstrating the discovery potential of the new experimental technique. This will make it possible to plan and develop a complete programme for future, missing-energy measurements with positron beams to fully investigate the space of the light dark matter parameters. The demonstration measure itself will, in fact, be potentially capable of probing an interval that is, now, unknown - but I don't expect any surprises in that sense, if not for the introduction of more competitive exclusion limits than the current ones.
Ultimately, I think that the allocation of ERC funding to a project linked to light dark matter research at accelerators may increase interest and involvement of the community in relation to this new investigative field, in which INFN already has a primary role with its participation and management of several dedicated experiments.

Andrea Celentano graduated from the University of Genoa in 2010, where he pursued his studies, obtaining his PhD in 2014. He has been a researcher with at the INFN Genoa division since 2017. His research activity began in the field of hadronic physics, as part of the CLAS experiment at Jefferson Laboratory in the United States. Since 2013 he has been involved in the new field of experimental research in light dark matter at accelerators,

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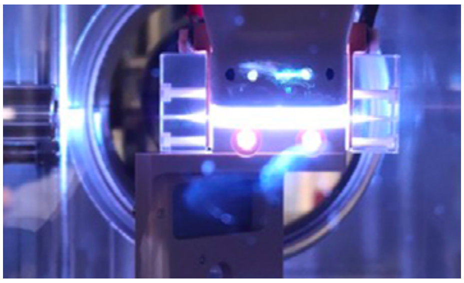
participating in the HPS (Heavy Photon Search) experiment at Jefferson Laboratory and proposing, at the same laboratory, the BDX experiment (Beam Dump eXperiment). Since 2015 he has been the promoter of a series of conferences: “Light Dark Matter at Accelerators” (LDMA). He also works on the design and construction of new detectors for particle physics experiments, including several electromagnetic calorimeters made of lead tungstate crystals, the technology of which underlies the detector proposed for the POKER project (POsitron resonant annihilation into darK mattER), awarded in 2020 with an ERC Starting Grant.

Lorenzo Bianchini, married and father of two girls, was born in Florence in 1985. After his three-year degree in Physics at the University of Florence, he continued his studies as an undergraduate student at the Scuola Normale Superiore of Pisa, obtaining his Bachelor’s and Master’s degrees in Physics in 2009. He obtained his PhD at the École Polytechnique in 2012 with a research thesis on the Higgs boson decaying to a tau lepton pair, work that directly contributed to the discovery of the Higgs particle by CMS. He continued his research as a post-doc at the ETH Zürich, mainly looking into measuring the ttH impact cross-section, a process that makes it possible to establish the direct pairing of the Higgs boson with the top quark. He has been a contract researcher at the INFN Pisa division since 2017, where he continued his engagement with the CMS experiment, both as far as regards the detector’s Phase 2 upgrade and physics analysis. In this last area, Bianchini has focused his interest on precise electroweak measurements, especially measuring the mass of the W boson.■



TECHNOLOGICAL RESEARCH

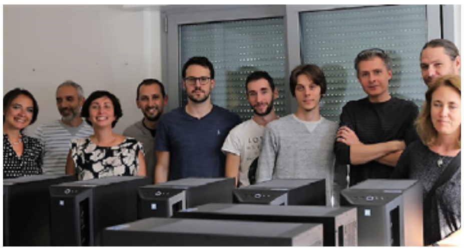
HIGH-QUALITY ELECTRONS ACCELERATED WITH PLASMA AT SPARC_LAB

One of the factors that most limits the application of plasma accelerators is the energy spread that the beam accumulates during acceleration in the plasma module. Recently, an experiment conducted by researchers of the SPARC_LAB group at the INFN Frascati National Laboratories demonstrated, for the first time, that it's possible to solve this problem and thus accelerate a beam of high-quality electrons. The results, recently published in Nature Physics, were obtained using an innovative technique that consists in imprinting the beam with an energetic correlation, with particles at the head having greater energy than those at the tail, before it enters the plasma. The energy spread induced by the plasma is, thus, pre-compensated, so that it is almost totally reduced upon exit from the module. This progress in the production of high-quality electron beams is fundamentally important because it makes the accelerated beam "usable" for applications such as, for example, Free-Electron Lasers (FEL). The work published describes, in addition, how the same method can be extended and applied to different energies and contexts, such as EUPRAXIA: a future, multidisciplinary, experimental research facility. These results thus represent an important goal, including for the use of plasma acceleration for applications dedicated to users in other scientific fields. ■

RESEARCH INFRASTRUCTURES

THE EINSTEIN TELESCOPE - THE GEOPHYSICAL SURVEYING CAMPAIGN TAKES OFF

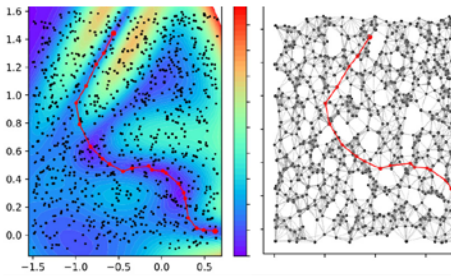
In Sardinia, the installation of the first network of seismic sensors on a large scale has begun for an extensive geophysical surveying campaign near the Sos Enattos metal mine, in Lula, the site Italy put forward to host the Einstein Telescope (ET). The ET is the observatory for third-generation gravitational waves, to which INFN, the Italian National Institute for Geophysics and Volcanology (INGV), and the National Institute for Astrophysics (INAF), and the Universities of Sassari and Cagliari are contributing. In detail, the campaign involves the installation of 15 seismometer stations for measuring vibrations in the earth that constitute seismic background noise, using techniques adapted from radar signal analysis. The aim is to identify and trace the evolution, over time, of the main sources - both natural and artificial - of seismic noise. The first surveys necessary for carrying out seismic tomography: an image of the subsoil obtained by recording the seismic waves artificially produced by a vibrating mass, activated by a special, heavy vehicle, will also be performed. With the involvement among others of the Physics Department of the University of Cagliari, the data will also be used to stydy the newtonian noise of the site, an effect of seismic noise that acts directly on the interferometer optics. The campaign will last two weeks and will have two goals: further quantify the exceptional “seismic silence” of the area, a fundamental requirement for the ET’s operations, and reconstruct the geology of the subsoil, with a view to planning the ET tunnel system. The results of these measurements will constitute one of the assessment criteria for the final choice between two site candidates (the other is located on the border of Belgium, Germany, and the Netherlands, in the region of Limburg). ■



APPLICATIONS

AN INNOVATIVE PROTOCOL FOR DISCOVERING POTENTIAL NEW DRUGS

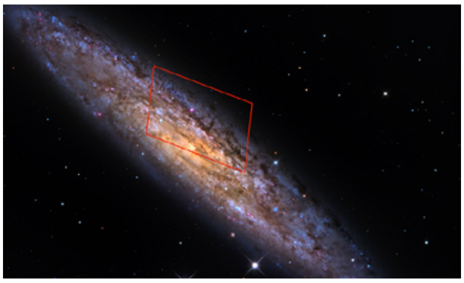
An innovative protocol for discovering potential new drugs has been developed by a broad, international team led by researchers from INFN, the University of Trento, the University of Perugia, the Dulbecco Telethon Institute, the Telethon Foundation. The Pharmacological Protein Inactivation by Folding Intermediate Targeting (PPI-FIT) protocol consists in identifying small molecules that can block the folding process of a protein involved in a pathological process, thus promoting its degradation through control mechanisms present in the cells. The PPI-FIT protocol, applied for the first time in the field of prion diseases, is the fruit of work with a strong multidisciplinary character, thanks to contributions that range from theoretical physics to IT, to medicinal chemistry, from biochemistry to cellular biology. The computational process, is founded on mathematical models developed in theoretical physics for studying subatomic phenomena, such as the quantum tunnelling effect, and suitable for simulating complex biomolecular processes, such as the folding and aggregation of proteins. The results obtained open a path forward for a new pharmacological paradigm, which is useful for modulating the levels of different factors involved in pathological processes. From an even broader perspective, the study suggests the existence of a generic mechanism for regulating protein expression, not considered until today, which acts at the level of folding paths. ■



APPLICATIONS

A QUANTUM ALGORITHM FOR SIMULATING THE TRANSFORMATIONS OF PROTEINS

A study conducted by three theoretical physicists of the University of Trento, which appeared yesterday in the Physical Review Letters, demonstrates the validity and the potential for an approach founded on the use of quantum computing in simulating structural changes to which proteins are subjected in the course of their lives, biological transformations on which the synthesis and activation of the latter depends. It is a result that highlights the great advantages that can be gained from the full development of quantum technologies. Over the last few decades, enormous steps forward have been taken in characterising the processes that involve the transformations of proteins and, more generally, of biological macromolecules, making use of computer simulations. In particular, the formation (folding process) or execution of the biological functions of proteins, which are composed of amino acid chains, is regulated by specific changes in their form. Precisely analysing and succeeding in providing structural variations, in shape and trajectory, of these biomolecules are, therefore, fundamental steps for developing advanced medical treatments for many diseases. ■

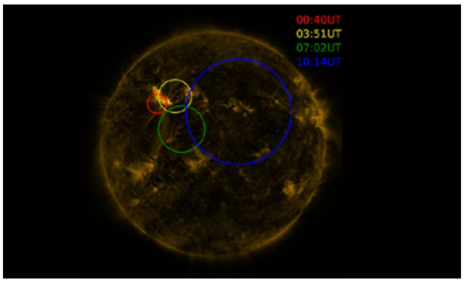


RESEARCH

THE FERMI SPACE TELESCOPE OBSERVES THE FIRST ERUPTION OF AN EXTRAGALACTIC MAGNETAR

Three studies published in Nature, Nature Astronomy, and The Astrophysical Journal Letters throw light on the origin of some Gamma Ray Bursts (GRB). Analysing the data obtained by European and American space probes following the detection of a GRB on 15 April 2020, the three studies trace the event back to the eruption of a magnetar: a neutron star with a very intense magnetic field, positioned in proximity to the Milky Way. The two detectors onboard NASA Fermi Gamma-Ray Space Telescope have also contributed to the measurement. These are the Gamma-Ray Burst Monitor (GBM) and the Large Area Telescope (LAT), an international collaboration in which INFN is an important member alongside the National Institute for Astrophysics (INAF) and the Italian Space Agency (ASI).

The characterisation of GRB 200415A (the name assigned to the event), and the accurate identification of its origin within galaxy NGC 253's disc, in the Sculptor constellation, were made possible thanks to the analysis and correlation of the data obtained by the space probes of the InterPlanetary Network (IPN) gamma ray burst location system. In particular, the study of data collected by GBM and LAT were essential for correctly classifying GRB 200415A in the context of the magnetar-type sources. While the first tool made it possible to highlight the peculiarities of the event's energy spectrum, which was completely different to that associated with gamma ray bursts generated by the fusion of neutron stars, the second detector enabled the identification of the signal's origin. ■



RESEARCH

THE FIRST CATALOGUE OF SOLAR FLARES OBSERVED IN THE GAMMA FREQUENCY

A first, detailed, and extensive catalogue of solar flares - violent explosions of electromagnetic radiation that take place in the sun's corona - has been presented in the journal Astrophysical Journal Letter Supplement (APJS). These solar flares were observed in the period from 2010 to 2018 in the gamma frequency by the Large Area Telescope (LAT), one of the two detectors installed onboard NASA's Fermi Gamma-ray Space Telescope. Italy participates in the international collaboration that is in charge of Fermi-LAT through contributions provided by INFN, the National Institute for Astrophysics (INAF) and the Italian Space Agency (ASI).

Fermi-LAT's great sensitivity has made it possible to observe some 45 solar flares that occurred in the period of maximum activity during the last solar cycle. This catalogue has increased the number of events known up to today by 10 times, making it possible to identify various, high-energy, solar photon emission mechanisms. In addition to the Sun's emission of gamma-ray bursts that last a few minutes, coinciding with flares detected in X-rays by other satellites, the space telescope registered events of a surprising extension and duration - up to 20 hours - that do not seem to have a counterpart in other wavelengths. The Fermi-LAT measurements have provided evidence that seems to confirm the hypothesis according to which extended emissions of the second type are generated by coronal mass ejections. ■

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GERDA PAVES THE WAY FOR LEGEND

Neutrinos are essential particles for understanding nature. Unfortunately, since they interact very little with matter, they are extremely evasive and it is, therefore, necessary to confront ever new technological challenges to be able to study them in depth. These are decisive scientific undertakings because understanding nature in detail would lead to a turning point in our knowledge. In particular, the study of an extremely rare, hypothetical process, which has still never been observed, called double beta decay without neutrino emission, would make it possible to understand whether the neutrino is a Majorana particle, or if it coincides with its antiparticle.

The GERDA (GERmanium Detector Array) experiment, at INFN Gran Sasso National Laboratories (LNGS), has investigated this process, using a technology based on Germanium crystals enriched from the germanium-76 Isotope. The experiment recently published its final results in the Physical Review Letters, determining the strictest limit on the half-life of this rare decay, fixing it at 1.8 x 10^{26} years, more than a million billion times the life of the universe. This exceptional result was obtained thanks to the extremely limited number of background events in the region of the signal, 5.2 x 10^{-4} counts/(keV kg yr): the lowest level ever obtained in the world in similar experiments. GERDA thus confirms that it has reached all the goals that were set for it, demonstrating the opportunity for a new generation of experiments with even greater sensitivity.

The history of research into double beta decay without neutrinos begins with a germanium detector of just 0.1 kg chosen for its excellent energy resolution by the research group of the INFN division and University of Milan, led by Ettore Fiorini. From that time, the experimental sensitivity has increased by a factor of one million. The continuous increase in the mass of detectors (which also constitute the source of decay), the strong reduction in background events in the region where the signal is expected, the optimisation of the underground installations for reducing the cosmic background radiation, and the enrichment of

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the detectors made of germanium-76 isotope by the natural fraction of 7.8% to approximately 90% were essential to this progress.

The GERDA experiment began operating in 2011 in the underground experimental facilities of the LNGS. In the final configuration of the experiment, 41 germanium detectors were used, comprising a total mass of 44.2 kg with an enrichment of approximately 87% of the germanium-76 isotope. The key to success was the use of pioneering techniques: unlike previous germanium experiments, the GERDA detectors were made to function “naked”, i.e., without their encapsulation, within a cryostat containing ultrapure liquid argon at a temperature of 87 degrees Kelvin (-186 degrees Celsius), which acts both as a cooling mechanism and as a shield for background events. This configuration, reducing the quantity of matter around the detectors, helps to minimise natural radioactivity. The active background suppression makes use of two complementary techniques. On the one hand, light detectors that can indicate whether a signal in the germanium detectors comes from natural background radiation are placed in the liquid argon. On the other hand, the study of the temporal profile of the signals gathered by the detectors makes it possible to further distinguish between background and signal events. Finally, detectors and cryostat are immersed in a container of ultrapure water as an additional screen against photons, neutrons and muons. While the equipment was operating, the GERDA collaboration developed detectors with a new design and innovative analysis to best make use of the equipment’s potential.

The GERDA experience leads us to believe that the background level could be reduced even further, so that it would be possible to design an experiment with a much higher mass of germanium capable of reducing the background events to the point that, for the whole data acquisition, lasting several years, no unwanted event would be registered in the interval of research fixed by the energy resolution of the detectors. The future LEGEND experiment has precisely this goal of increasing the sensitivity of the half-life of the double beta decay without neutrinos to 10^{28} years (one hundred times more than the GERDA result). In a first phase, called LEGEND-200, in the same facility as GERDA’s, 200 kg of germanium detectors will be used. ■

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