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Editorial

Editorial for the Special Issue "Neutrinoless Double Beta Decay"

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The present Special Issue is dedicated to the long-sought-after nuclear process known as Neutrinoless Double Beta Decay (NDBD), a nuclear transition characterized by the simultaneous decay of two neutrons into protons and electrons, without the emission of neutrinos. This form of nuclear decay violates the residual symmetry of the Standard Model B-L and is considered a portal to new physics. Its discovery would establish that neutrinos and anti-neutrinos coincide, thus being Majorana fermions. It would also constitute a matter-creating process, shedding light on theories explaining the matter/antimatter asymmetry in the universe [1].

The discovery that neutrinos are massive has given an important boost to the experimental search for NDBD. Several experiments operating different detection techniques have produced data in recent decades, and many are currently running. A new round of projects is being prepared, the next experimental goal being to fully cover the range of Majorana masses corresponding to the inverted hierarchy scenario for neutrino masses.

At the same time, advances in nuclear theory are paving the way to connecting experimental results with the underlying new physics, disentangling the effects of nuclear physics from unknown lepton-number-violating mechanisms.

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The contributions to this Special Issue cover theoretical aspects of NDBD and neutrino masses, as well as reviews of the current search status and perspectives on future experimental efforts, in particular for the isotopes of tellurium, germanium and cadmium. In addition, the subject of NDBD nuclear matrix elements (NMEs) is deeply investigated, both from a theoretical point of view and with an experimental approach, exploiting charge exchange reactions as probes. Concerning experimental searches for the elusive NDBD, the constant struggle against background radiation, which is common to the various experimental techniques, is examined in several contributions, including a detailed study on the effect of the cosmogenic activation of materials.

Paper [2] can be considered as the introductory contribution to this Special Issue. It discusses the debate over the Majorana vs. Dirac nature of neutrino masses: one of the last outstanding questions of modern neutrino physics, and crucial to our understanding of the origin of small neutrino masses. This work reviews the basic arguments in favour of the Majorana nature of massive neutrinos and also gives a brief discussion of the phenomenological theory of NDBD, together with recent experimental data and a discussion of the sensitivity of future experiments.

Furthermore, on the theory side, paper [3] presents a review of the most recent and advanced shell-model calculations of NDBD nuclear matrix elements, in the light-neutrino-exchange theoretical approach. The shell model is considered the basic framework of the microscopic description of the nucleus and has produced reliable results among the various computational models adopted to solve the many-body nuclear problem.

Given that NDBD has so far eluded discovery, it is possible to use the two-neutrino DBD, the SM allowed counterpart of the neutrinoless process, to directly compare experimental and calculated values for nuclear matrix elements. Paper [4] reviews the status, as of 2020, of all existing positive results on two-neutrino double beta decay and two-neutrino double electron capture in different nuclei. From the measurement of such half-lives, the effective NMEs for the above transitions can be calculated, and recommended values are reported in the paper to serve as a reference for theoretical calculations.

Another possible experimental approach to provide valuable information to constrain the calculations of NMEs is the study of charge exchange reactions. Paper [5] gives an overview of the role of such reactions in this scenario, focusing on second-order processes such as double charge exchange (DCE) reactions, which change the nuclear charge by two units, keeping the mass number unvaried, in line with the $\beta\beta$-decay. The present status of the field appears promising, with accurate cross-section measurements that could be performed in the near future.

An interesting observation of such measurements is the DCE cross-section for the transition to the ground state of the residual nucleus, as the corresponding nuclear matrix element could be connected that of the NDBD, as it links the same initial and final states. The NUMEN heavy ion multidetector, as described in [6], is designed for the study of DCE reactions, and in this work focus is given to the challenging experimental apparatus which is currently under construction in order to fulfil the requirements of the NUMEN experiment.

On the topic of current and future NDBD experimental searches, the contributions [7] and [8] describe the development of the Ge semiconductor technique in the search for the NDBD, highlighting the strengths and weaknesses. The final results from the GERDA and MAJORANA experiments are reported, as well as the design of the future LEGEND 1000 project, and the LEGEND-200 demonstrator, currently in its commissioning phase at LNGS.

Alongside germanium, tellurium is one of the leading candidates as a source material for NDBD experiments. Tellurium isotopes feature a high natural abundance and have been employed as $\beta\beta$ emitters in multiple experiments over the past years. In this regard, contribution [9] provides a review of the latest rare decay searches using tellurium isotopes, where theoretical expectations are compared with existing results and prospects from running and future experiments.

Contribution [10] presents new improved half-life limits for the double beta decay processes of the isotope ^{106}Cd using a cadmium tungstate scintillator enriched in 106Cd at 66% (^{106}CdWO$_4$). The studied decays are “double beta plus” (double electron capture (2EC), electron capture with positron emission (ECβ^+), and double positron decay (2β^+)), which have the potential to clarify the possible contribution of the right-handed currents to the NDBD rate, and the interesting possibility of a resonant 0ν2EC process.

Finally, contribution [11] discusses an issue that is becoming more and more crucial in the struggle against the radioactive background of future NDBD experiments: the cosmogenic activation of materials. Experiments intended to detect rare processes such as NDBD must be conducted deep underground and in ultra-low background conditions. Long-lived radioisotopes produced by the previous exposure of materials to cosmic rays on the Earth’s surface or even underground can become problematic for the required sensitivity. The paper considers target materials such as germanium, tellurium, and xenon, as well as other commonly selected materials such as copper, lead, stainless steel, and argon, in order to predict the effect of cosmogenic activation in present and future double beta decay projects based on different types of detectors.

This Special Issue provides an interesting and well-balanced mix of the theoretical and experimental aspects of the search for NDBD, and gives a fair overview of the open issues on which future research must focus. The prize at stake is the answer to one of the fundamental questions of modern physics: are neutrinos Majorana or Dirac particles?

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