Recommendations

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Silvia Pascoli
IPPP, Durham University

- ***Recommendation 1. The search for neutrinoless double beta decay searches is a top priority in particle and astroparticle physics.***

The discovery of neutrino masses and mixing, implied by neutrino oscillations, is so far the only particle physics evidence of physics beyond the Standard Model (SM). It has opened new key questions, among which establishing the nature of neutrinos is arguably the most important. The latter is intrinsically related to the conservation of lepton number, which is related to the fundamental symmetries of nature, the origin of neutrino masses in theories beyond the Standard Model and the generation of the observed matter-antimatter asymmetry in the Universe via the leptogenesis mechanism. Generically, neutrinoless double beta decay is the most sensitive probe of lepton number violation. It is mediated by the 3 light massive neutrinos, if they are of Majorana type, with half-lives which may be at reach in current and future experiments. The theoretical predictions depend on the values of neutrino masses, whether they are with normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$) ordering, and on the CP violating phases. They can also receive contributions from other lepton number violating processes, e.g. sterile neutrinos, in extensions of the SM.

- ***Recommendation 2. A sustained and enhanced support of the European experimental programme is required to maintain the leadership in the field, exploiting the broad range of expertise and infrastructure and fostering existing and future international collaborations.***

Key technologies in the search for neutrinoless double beta decay have been conceived, developed and demonstrated in Europe: germanium diodes operated in liquid argon with high energy resolution and multi-site event rejection; pure and scintillating bolometers capable of studying at least four different isotopes with high energy resolution and particle identification; gaseous Xenon TPC capable of joining good energy resolution with topological reconstruction of the events and, in future, final state identification. Other developments regard the use of room temperature semiconductor detectors and the synergies between dark matter search and double beta decay searches in Xe-based experiments. The most promising searches based on these technologies should be supported to ensure European leadership and at the same time to foster international cooperation given the worldwide efforts in this field. The potential of European laboratories to host next-generation double beta decay experiments should be exploited.

• *Recommendation 3. A multi-isotope program at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.*

The current objective of the experimental search for neutrinoless double beta decay (DBD0ν) is to explore deep into the inverted ordering region of the neutrino mass pattern. Several proposed next-generation projects aim at this goal. Some of them can in principle fully cover this region and detect DBD0ν even in case of direct ordering, provided that the lightest neutrino mass is larger than 10–20 meV.

Future projects can be broadly classified into two categories: experiments using a fluid-embedded DBD0ν source (featured by large sensitive masses and easy scalability) and experiments using a crystal-embedded DBD0ν source (featured by high energy resolution and efficiency). In the first class we have Xe-based TPC projects like nEXO (evolution of the closed EXO-200), NEXT-HD (evolution of imminent NEXT-100), and PandaX-III-1t (evolution of the foreseen PandaX-III-200). This class includes also experiments which dissolve the source in a large liquid-scintillator matrix exploiting existing infrastructures like KamLAND2-Zen (evolution of the current KamLAND-Zen-800) and SNO+-phase-II (evolution of the imminent SNO+-phase- I). In the second class we have experiments based on germanium diodes like LEGEND-1000 (evolution of the current GERDA and MAJORANA and of the planned LEGEND-200) and those which exploit the bolometric technique, like the multi-step AMoRE program (AMoRE-I and AMoRE-II, which represent the evolution of the current AMoRE pilot), and CUPID, which is based on the large experience gathered by CUORE and the demonstrators CUPID-Mo and CUPID-0, which are all collecting data.

In this rich landscape, the most prominent projects with a strong European component are CUPID, LEGEND-1000 and NEXT-HD. Featured by a planned 3 σ discovery sensitivity that, at least for some matrix element calculations, reaches below 20 meV for $m_{\beta\beta}$, these projects can ensure Europe a forefront position in the international scenario. They study three different isotopes (^{100}Mo, ^{76}Ge and ^{136}Xe respectively) with quite different approaches, offering a large complementarity that is a bonus for such a challenging research. A multi-technology approach is necessary to mitigate the risks of individual experiments and to corrobo- rate the findings, given the experimental challenges posed. The use of multiple isotopes may allow to identify the mechanism behind the process, whether mediated by light neutrino masses or due to some exotic physics.

- ***Recommendation 4. A programme of R&D should be devised on the path towards the meV scale for the effective Majorana mass parameter.***

If the neutrino mass ordering is normal and the lightest neutrino mass is below 10-20 meV, only experiments with zero background in the tens of tons scale have a chance to detect neutrinoless double beta decay if the light neutrino mass mechanism is dominant. This poses a formidable challenge that no technology is capable of facing at the moment. However, extensions of the present approaches or totally new ideas could in principle achieve this elusive target if supported by an adequate R&D program. These R&D activities should be funded in order to prepare right now the medium term future of double beta decay search. Of course, the required large scale enrichment remains by itself a major challenge, which could probably be overcome only by developing a dedicated international facility as a part of the research program itself.

- ***Recommendation 5. The European underground laboratories should provide the required space and infrastructures for next generation double beta decay experiments and coordinate efforts in screening and prototyping.***

In order to establish a multi-technology and multi-isotope DBD0ν physics program extensive underground space to host the DBD0ν-experiments is necessary. Facilities, not only in Europe, are encouraged to support this rich physics strategy by providing the necessary underground space (including upgrading existing facilities) as well as onsite expertise in low-background techniques to guarantee an effective and timely implementation of the experiments. Close coordination between the European underground laboratories for hosting prototype detectors and low-background screening is mandatory.

- ***Recommendation 6. The theoretical assessment of the particle physics implications of a positive obser- vation and of the broader physics reach of these experiments should be continued. A dedicated theoretical and experimental effort, in collaboration with the nuclear physics community, is needed to achieve a more accurate determination of the NMEs.***

Last but not least, once a positive signature is found, lepton number violation will be established and a key question will be to determine the physics mechanism behind it. A strong theoretical effort should be devoted to continue to explore different theoretical models behind neutrinoless double beta decay and its complementarity with other experimental searches e.g. for heavy sterile neutrinos, left-right models at colliders, leptoquarks etc. Consequently, this will allow to extract the information from the measurement of the half life. Most interestingly, in the case of the simplest mechanism of light neutrino exchange, this would give information on neutrino masses and, at least in principle, on Majorana CP violation, with a strong complementarity with the determination of neutrino masses from cosmology. Such plan requires to extract the effective Majorana mass parameter with high precision, for which nuclear matrix elements need to be evaluated. The computation of nuclear matrix elements is challenging and currently is affected by an uncertainty which is typically quantified in a factor of 2-3. New developments are very promising and exploit ab-initio computations. An enhanced effort is required and a stronger interactions between the particle physics and nuclear community would be highly beneficial. Dedicated experiments may be required.

Thanks to the large mass, low background and high detector performances, the new generation double beta decay experiments will be also sensitive to a certain number of other physical processes that allow experimental investigation with unprecedented sensitivities. Alternative double beta decay modes, some exotic processes predicted by the extensions of the Standard Model, validation of fundamental physics principles and, most important, the search for interaction of Dark Matter particles. The investigation of all these possible physics channels indicates that the designed approaches could be considered as multipurpose experiments, for which neutrinoless double beta decay is the main goal, but also other important achievements could be also considered of extreme scientific importance.