IL NUOVO CIMENTO **47 C** (2024) 346
DOI 10.1393/ncc/i2024-24346-x

Colloquia: MAYORANA 2023

Neutrinoless double beta decay: A brief view of the field

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received 6 August 2024

Summary. — Foremost among the open questions regarding neutrinos are whether they are their own anti-particles, hence Majorana fermions, and the magnitude of their rest mass, in particular also why they are so much lighter than the charged leptons. The most sensitive probe of the Majorana nature of neutrinos is a remarkable rare nuclear transition, neutrinoless double beta decay ($0\nu\beta\beta$), in which two electrons and no neutrinos are emitted. Its observation would not only demonstrate that neutrinos are Majorana fermions, but would also establish lepton number violation. A large number of $0\nu\beta\beta$-decay experiments, using different candidate isotopes and detection techniques for the two outgoing electrons, are operational or planned to be constructed in deep-underground laboratories. Their extraordinary goal is to observe but a handful of events at the Q-value of the decay, and thus to reduce radioactivity-induced backgrounds to unprecedentedly low levels. Current results limit the $0\nu\beta\beta$-decay half-lives to values larger than 10^{25-26} years, while experiments taking data, under construction or in advanced planning stage aim to probe the 10^{27-28} years regime. In parallel, new ideas on the possibility to build much larger detectors to explore the half-life regime beyond 10^{28-29} years are being put forward. Here we give a brief view of the current status of the field, and of future developments including the main experimental challenges.

1. – Introduction

Neutrinos are among the most abundant particles in the universe, yet notoriously difficult to detect. Almost a hundred years after they were proposed by Wolfgang Pauli, and about seventy years after their discovery([1]), several of their properties remain unknown. Foremost among these are the questions: What is the rest mass of neutrinos,

([1]) Wolfgang Pauli proposed the existence of neutrinos in 1930, in an often quoted letter addressed to a group of nuclear physicists attending a conference in Tübingen on December 4 of that year [1]. It took more than 20 years until Clyde Cowan and Frederick Reines proved the existence of the neutrino experimentally [2, 3]. Enrico Fermi took Pauli's idea seriously and developed a theory of weak interactions in 1934 [4]; he also coined the term neutrino, the "little neutral one".

and are neutrinos their own anti-particles, thus Majorana fermions([2])? This property is connected to the origin of their mass, and thus to the question of why neutrinos are so much lighter than the charged fermions. Many extensions to the Standard Model (SM) of particle physics predict Majorana neutrinos [7].

The most sensitive and perhaps only practical probe for the Majorana nature of neutrinos is an exceedingly rare and as of yet unobserved nuclear decay process called neutrinoless double beta decay ($0\nu\beta\beta$)([3]). The observation of this decay would not only demonstrate that neutrinos are Majorana fermions, but would also establish lepton number violation. While both baryon and lepton numbers are conserved in the SM, baryon number violations predicted by SM extensions required to generate the observed matter-antimatter asymmetry in the early universe may come from lepton number violating processes, also known as leptogenesis [7]. Hence the nature of neutrinos is deeply connected to the question of why there is more matter than antimatter in the observable universe.

2. – Neutrinoless double beta decay

In a $0\nu\beta\beta$-decay process, a nucleus with mass number A and charge Z is transformed into another nucleus with the same mass number, but with a nuclear charge increased by two units. Two electrons are emitted in the process and no neutrinos:

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-. \tag{1}$$

Since the total lepton number changes by a factor of two in this decay, its occurrence would disprove this conservation law. The experimental observable is the decay rate, which is inversely proportional to the half-life, and the principal challenge is the ability to measure the extremely long half-lives predicted by current estimates and experimental constraints. These are between $\mathrm{T}^{0\nu}_{1/2} \sim 10^{26} - 10^{28}$ y for the inverted neutrino mass ordering, and $\mathrm{T}^{0\nu}_{1/2} > 10^{28}$ y for the normal mass ordering scenario. For the case of exchange of light Majorana neutrinos, the mechanism which dominates the rate of the process [10], the decay rate and thus the half-life are related to the neutrino mass scale as follows [11]:

$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}, \tag{2}$$

where $G^{0\nu}(Q,Z)$ is the phase-space integral, scaling with the fifth power of the Q-value of the decay, g_A is the axial vector coupling, $M^{0\nu}$ is the nuclear matrix element, $\langle m_{\beta\beta}\rangle$ is the effective Majorana neutrino mass, and m_e is the mass of the electron. The effective

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([2]) This possibility was first suggested by Ettore Majorana, born in Catania in August 1906, in his 1937 paper [5] in Nuovo Cimento, at a time when neutrinos were still hypothetical. Majorana mysteriously disappeared shortly afterwards, in 1938: "Ettore Majorana non verrà mai trovato: né vivo, né morto." [6].

([3]) The decay with two neutrinos was first proposed by Maria Goeppert-Mayer in 1935 [8], while the decay with no neutrinos was first discussed by Wendell H. Furry in 1939 [9], soon after Majorana had proposed that neutrinos could be their own antiparticles.

Majorana neutrino mass parameterises the decay rate in terms of the neutrino mass eigenstates, mixing angles, and CP-violating phases. It can be expressed, as an example, as a function of the lightest mass state, for the two mass orderings, as shown in fig. 1.

The predicted values depend critically on the neutrino mass spectrum, and on the two unknown Majorana phases in the neutrino mixing matrix. Given the neutrino oscillation data (we refer to [12] for the latest fits), we can see that the effective Majorana mass is strictly larger than zero for the inverted mass ordering case. For this case, one can calculate the lowest $m_{\beta\beta}$ value, minimised with respect to the unknown Majorana phases, to obtain $m_{\beta\beta}^{\min} \sim 18\,\mathrm{meV}$ [13]. This in turn corresponds to an upper bound on the half-life of $\mathrm{T}_{1/2}^{0\nu} \sim 10^{27}$–$10^{28}$ y, depending on the values of the nuclear matrix elements. These vary by a factor 2–3 for a given mass number, causing the largest uncertainty on extracting the effective Majorana mass values (we refer to ref. [14] for a recent review).

3. – Experimental requirements and approaches

Thirty-five even-even nuclei are candidates for $0\nu\beta\beta$-decay and, given the dependance of the decay rate on the Q-value, it is of advantage to use isotopes with high Q-values. This in general is also correlated to a lower background rate in the region-of-interest (ROI). There are 11 isotopes with Q-values above 2 MeV and, with the exception of ^{48}Ca and ^{130}Te, which have a low (0.2%) and high (34.5%) natural abundance, respectively, the natural abundances are in the range 3–12%. Thus, in most cases, enriched material are employed in experimental searches for $0\nu\beta\beta$-decay.

Experiments aim to measure the half-life of the decay which, for a non-zero background experiment, scales as [15]:

$$T_{1/2}^{0\nu} = \ln 2 \frac{a \epsilon f N_A}{1.64 M_A} \sqrt{\frac{Mt}{B \Delta E}}, \tag{3}$$

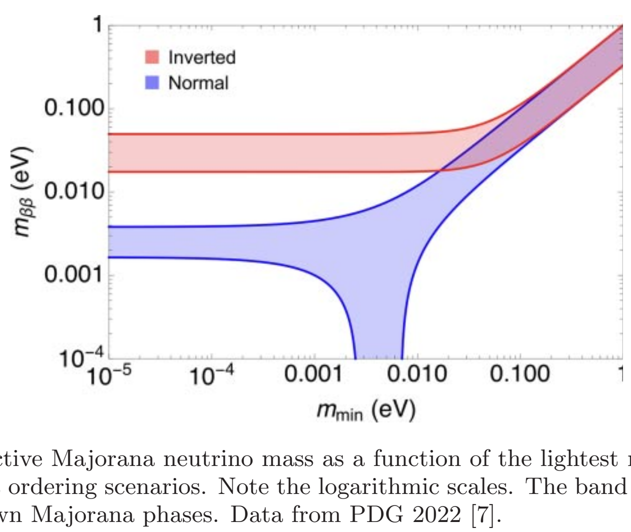

Fig. 1. – The effective Majorana neutrino mass as a function of the lightest mass state, for the two different mass ordering scenarios. Note the logarithmic scales. The band widths are mainly due to the unknown Majorana phases. Data from PDG 2022 [7].

with a being the abundance, ϵ the efficiency for observing the two electrons, f the fraction of the signal in the ROI, N_A the Avogadro constant, M_A the molar mass, M the mass of the source, t the measuring time, B the background rate in the ROI and ΔE the energy resolution at the Q-value. In the zero background regime, the half-life sensitivity scales linearly with the exposure Mt. This is illustrated in fig. 2, which shows the half-life sensitivity for a ^{76}Ge experiment, LEGEND [16], as a function of exposure for different background scenarios, including the background-free case.

4. – Current and future experiments, technological challenges

Experimental searches use different isotopes and a variety of detection techniques. They require an ultra-low background level and an excellent energy resolution, for the signature of the decay is a delta-function at the Q-value. A good energy resolution is thus required to identify the peak and in particular also to distinguish between the neutrinoless mode from the inescapable SM process. Of advantage are also a high isotopic abundance and a high efficiency for detecting the two electrons emitted in the decay.

An overview of the main techniques, with experiments broadly aiming to detect ionisation, scintillation or phonon signals following a $0\nu\beta\beta$-decay, is shown in fig. 3. Most experiments follow a calorimetric approach, where the decaying isotope is contained in a scintillating material (liquid, gas or crystal), in a semiconductor or in a bolometer, and the sum energy of the two electrons is measured. Tracking detectors aim to observe the two electrons and thus the event topology, either with thin foils as source and the electrons detected separately, or in a high-pressure, gaseous time projection chamber (TPC). Some experiments measure both, scintillation and phonons, for background identification, or scintillation and ionisation in a TPC, for an improved energy resolution, in addition to background discrimination.

All experiments are operated deep underground to reduce backgrounds from cosmic ray muons, and are surrounded either by active or passive shields to mitigate radioactivity-induced backgrounds. Active shields do not only allow for background identification on an event-by-event basis, but also for an *in situ* characterisation and

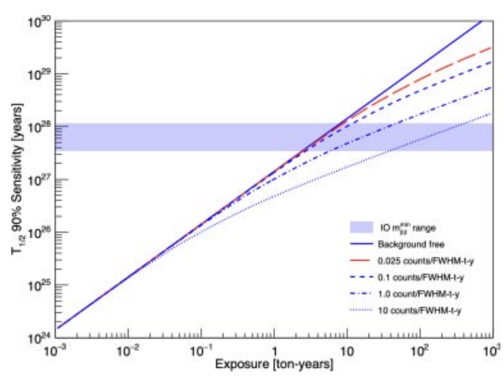

Fig. 2. – The sensitivity to the half-life of $0\nu\beta\beta$-decay as a function of exposure Mt, for different background scenarios, including the background-free case (solid line), for the LEGEND ^{76}Ge experiment. The expected half-life region for the inverted neutrino mass ordering scenario (see fig. 1) is shown as a shaded horizontal band. Figure from [16].

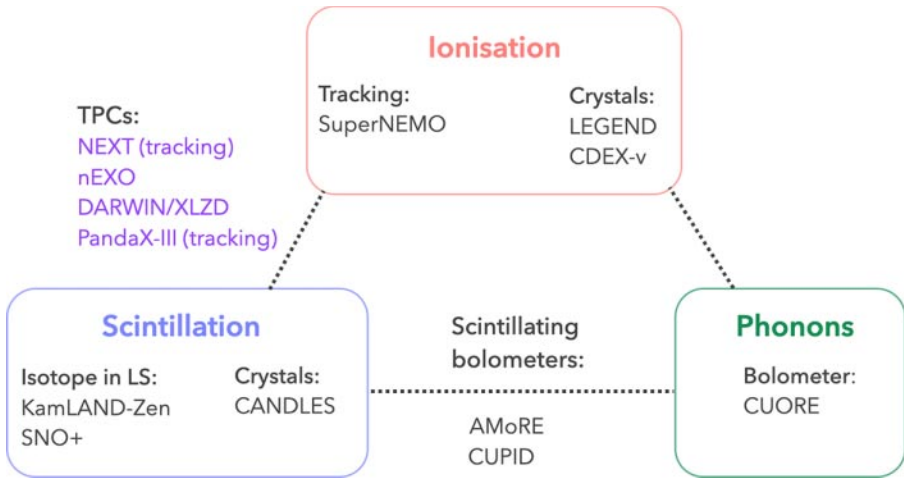

Fig. 3. – Overview of the main experimental techniques with some current and future experiments searching for $0\nu\beta\beta$-decay (more details in table I). The observation of scintillation and phonons, or scintillation and ionisation in a TPC, allow for background identification, and for an improved energy resolution (compared to scintillation-only detectors), respectively.

temporal monitoring of these sources. The exposure of the target and surrounding materials to cosmic rays at the Earth's surface must be minimised, since spallation reactions can produce long-lived radioactive isotopes. In addition, the neutron flux from (α, n) and ^{238}U fission reactions in detector materials, where the *alpha*-particles are from the natural decay chains of ^{232}Th and ^{238}U, must be minimised, since neutron capture reactions can produce *in situ* activation of the target or materials close to it. The ultimate background for the $0\nu\beta\beta$-decay search will be due to irreducible elastic neutrino-electron scatters from solar ^{8}B neutrinos. This component can however be mitigated via directional information, a possibility which is explored via Cherenkov light detection. After decades of intensive searches, there is no experimental evidence for $0\nu\beta\beta$-decay so far. At present, the most stringent lower limits on the half-life are 2.3×10^{26} y (^{136}Xe, KamLAND-Zen [17]), 1.8×10^{26} y (^{76}Ge, GERDA [18]) and 2.5×10^{25} y (^{130}Te, CUORE [19]). These translate into upper limits on the effective Majorana neutrino mass in the range (0.08-0.18) eV, depending on the value of the nuclear matrix elements. Currently operating and some planned experiments are listed in table I. For recent reviews and current status of the field we refer to [7, 14, 20, 21]. In general, experiments acquiring data or under construction aim for discovery sensitivities around $\mathrm{T}^{0\nu}_{1/2} \sim 10^{27}$ y, while next-generation experiments are designed to reach the $\mathrm{T}^{0\nu}_{1/2} \sim 10^{28}$ y regime. To grasp the extraordinary challenge in measuring these half-lives, it is instructive to consider the related count rates: a half-life of $\mathrm{T}^{0\nu}_{1/2}=10^{28}$ years corresponds to a rate of only about 0.5 events per tonne of isotope and year. A helpful, albeit approximate formula to connect the half-life to the Majorana neutrino mass scale is:

$$T^{0\nu}_{1/2} \approx 10^{27-28} \left(\frac{0.01\,\mathrm{meV}}{\langle m_{\beta\beta}\rangle}\right)^2 . \tag{4}$$

TABLE I. – *Currently operating (or in commissioning phase) and some future $0\nu\beta\beta$-decay experiments. The underground location (the cases where it is still open are indicated with "TBD"), employed technique and isotope, together with the abundance (either natural, or after enrichment) and total isotope mass are shown.*

Experiment	location	technique	isotope, abundance	isotope mass
Current				
AMoRE-I	Y2L	Bolometers	^{100}Mo, 96%	3 kg
CANDLES	Kamioka	Scint. crystals	^{48}Ca, 0.2%	0.35 kg
CUORE	LNGS	Bolometers	^{130}Te, 34%	206 kg
LEGEND-200	LNGS	HPGe in LAr	^{76}Ge, 90%	180 kg
KAMLAND-Zen	Kamioka	Liquid scintillator	^{136}Xe, 91%	745 kg
NEXT-100	LSC	HP-GXe	^{136}Xe, 90%	87 kg
SuperNEMO-Demo	Modane	Tracker, calorimeter	^{82}Se, 9.2%	7 kg
Future				
AMoRE-II	Yemilab	Bolometers	^{100}Mo, 96%	110 kg
CDEX-300ν	CJPL	HPGe in LArn	^{76}Ge, >86%	225 kg
CUPID	LNGS	Scint. bolometers	^{100}Mo, 97%	240 kg
DARWIN/XLZD	TBD	LXe TPC	^{136}Xe, 8.9%	3.6–7.1 t
LEGEND-1000	LNGS	HPGe in LAr	^{76}Ge, 90%	1 t
KAMLAND2-Zen	Kamioka	Liquid scintillator	^{136}Xe, 91%	1 t
NEXT-HD	TBD	HP-GXe	^{136}Xe, 90%	1.2 t
nEXO	SNOLAB	LXe TPC	^{136}Xe, 90%	4.8 t
PandaX-III	CJPL	HP-GXe	^{136}Xe, 90%	140 kg–1 t
SNO+	SNOLAB	Liquid scintillator	^{130}Te, 34%	1.3 t
SuperNEMO	Modane	Tracker, calorimeter	^{82}Se, 9.2%	100 kg

Apart from the future projects shown in table I, intense R&D activities on opaque scintillators, on detecting both scintillation and Cherenkov light in large liquid scintillators, on new type of bolometers with position resolution or Cherenkov light detection, as well as on the *in situ* identification of the barium ions produced in the $0\nu\beta\beta$-decay of ^{136}Xe is ongoing. Additionally, new ideas on loading candidate isotopes (*e.g.*, Te, Xe, Zr, Se, Mo) in large-scale, organic liquid scintillators, or operating 10 kton-scale liquid argon TPCs with Xe doping are being explored, with the goal of reaching the 10-100 t isotope scale. Ideas for kton-scale liquid xenon detectors, which would require new approaches for acquiring the xenon, are being put forward as well. We refer to [14] for a detailed overview. As experiments increase in size and complexity, a range of technological challenges, which are highly dependent on the employed detector type, will need to be addressed. Common to all approaches is the challenge to further decrease the radioactivity of detector or target materials to values well below 1 μBq/kg, and concomitantly to devise more sensitive radio-assay techniques.

5. – Conclusions

The study of neutrino properties is one of the most fascinating in science today. Notwithstanding the impressive progress in understanding their interactions over the past decades, many important questions remain to be settled. Chief among these are the magnitude of their rest mass and the question of why they are so much lighter than other elementary particles, as well as their nature. The observation of an extraordinarily rare nuclear decay process, $0\nu\beta\beta$-decay, would provide the answer to these questions, establishing lepton number violation and evidence for Majorana neutrinos. This search is one of the most challenging undertakings today. The difficulty lies in the ultra-low decay rates, requiring the elimination of all potential backgrounds, a large amount of source material, as well as an excellent energy resolution to distinguish the neutrinoless mode from the inevitable SM process. After decades of development, current-generation detectors probe half-lives above 10^{26} years, and experiments under construction and advanced planning will increase the sensitivity by one and two orders of magnitude, respectively. In addition, several ideas on the possibility to build much larger detectors to explore the half-life regime beyond 10^{28-29} years were put forward.

We conclude by noting that the study of neutrinos and of their properties will not only lead to a more complete understanding of elementary particle physics, and in particular of physics beyond the SM, but has implications in a wide range of other fields, from astrophysics and cosmology to low-energy nuclear physics and geophysics.

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The author acknowledges support from support from the University of Zurich, from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme, grant agreement No. 742789 (*Xenoscope*) and from the SNF via grants 200020-219290 and 20FL20-216572. The author would like to thank the organisers for an inspiring school in a beautiful setting.

REFERENCES

[1] ETH-Zurich, *ETH Library*, `https://library.ethz.ch/`, accessed 2024-01-15.
[2] Reines F. and Cowan C. L., *Phys. Rev.*, **92** (1953) 830.
[3] Cowan C. L., Reines F., Harrison F. B., Kruse H. W. and McGuire A. D., *Science*, **124** (1956) 103.
[4] Fermi E., *Z. Phys.*, **88** (1934) 161.
[5] Majorana E., *Nuovo Cimento*, **14** (1937) 171.
[6] Russo B., *Ettore Majorana, Un giorno di marzo* (Flaccovio Editore) 2005.
[7] Workman R. L. *et al.*, *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[8] Goeppert-Mayer M., *Phys. Rev.*, **48** (1935) 512.
[9] Furry W. H., *Phys. Rev.*, **56** (1939) 1184.
[10] de Gouvea A. and Jenkins J., *Phys. Rev. D*, **77** (2008) 013008.
[11] Engel J. and Menéndez J., *Rep. Prog. Phys.*, **80** (2017) 046301.
[12] Esteban I., Gonzalez-Garcia M. C., Maltoni M., Schwetz T. and Zhou A., *J. High Energy Phys.*, **09** (2020) 178.
[13] Agostini M., Benato G., Detwiler J. A., Menéndez J. and Vissani F., *Phys. Rev. C*, **104** (2021) L042501.
[14] Agostini M., Benato G., Detwiler J. A., Menéndez J. and Vissani F., *Rev. Mod. Phys.*, **95** (2023) 025002.
[15] Avignone F. T., King G. S. and Zdesenko Y. G., *New J. Phys.*, **7** (2005) 6.
[16] LEGEND Collaboration (Abgrall N. *et al.*), arXiv:2107.11462 (2021).
[17] Abe S. *et al.*, *Phys. Rev. Lett.*, **130** (2023) 051801.
[18] Agostini M. *et al.*, *Phys. Rev. Lett.*, **125** (2020) 252502.
[19] Adams D. Q. *et al.*, *Nature*, **604** (2022) 53.
[20] Adams C. *et al.*, arXiv:2212.11099 (2022).
[21] Giuliani A., Gomez Cadenas J. J., Pascoli S., Previtali E., Saakyan R., Schäffner K. and Schönert S., arXiv:1910.04688 (2019).