Neutrinos : désintégration double-béta

Neutrinos: double-beta decay

Proposed about eighty years ago, few years after Majorana's description of fermions in a relativistic quantum field theory, the neutrinoless double beta decay ($0\nu\beta\beta$) is a very rare nuclear decay in which a nucleus (A, Z) transforms into its isobar $(\mathrm{A}, \mathrm{Z}+2)$ with the only emission of two electrons:

$$(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^-$$

The equivalent decays modes in which the electrons are replaced by positrons or by an electron capture are also possible, and are characterized by a lower experimental sensitivity.
The distinctive features of the neutrinoless double beta decay are of particular importance in the context of the Standard Model of particle physics (SM):

- it violates the lepton number by two units, supporting the possibility that neutrinos played an important role in the creation of the matter-antimatter asymmetry in the universe;
- it can only happen if neutrinos are Majorana fermions, i.e. they coincide with their anti-particles;
- it would imply that neutrino are Majorana massive particles, and it would allow to set constraints of their mass scale (complementary to direct and cosmological ones);
- it can help shading light onto the mass hierarchy problem, even if not observed;
- it represents a unique possibility to measure the neutrino Majorana phases.

Relevant in this contest is also the double beta decay with two neutrinos in the final state ($2\nu\beta\beta$), which oblige the lepton number conservation the and is allowed by the SM.

Despite the large number of possible theoretical scenarios, the most appealing mechanism for $0\nu\beta\beta$ is the exchange of light Majorana neutrinos. This is due both to the experimental indication of the existence of three families of neutrinos with a light mass and to the theoretical assumption that the scale of new physics beyond the SM is much higher than the electroweak scale.
Among the alternative mechanisms, particularly interesting are the case of a heavy right-handed (RH) neutrino with a mass of $\mathcal{O}(10\,\mathrm{GeV})$, and the case of RH currents and (heavy) intermediate bosons. For both models, portion of the phase space can be probed by direct searches, e.g. those conducted at the CERN LHC.

Theoretical framework

Without encompassing a detailed description of the theoretical framework of the $0\nu\beta\beta$ decay, it is of interest to write explicitly the half-life of the process for the case of a light-neutrino exchange:

$$t^{1/2} = G_{0\nu}\, |\mathcal{M}|^2\, \frac{|m_{\beta\beta}|^2}{m_\mathrm{e}^2},$$

where $G_{0\nu}$ is the phase space integral, $\mathcal{M}$ is the nuclear matrix element (NME) and $m_{\beta\beta}$ is the so called "effective neutrino mass", a coherent linear combination of the neutrino masses given by $m_{\beta\beta} = \sum_{k=1}^{3} |U_{ek}^{L}|^2 m_k e^{i\varphi k}$, where U is a unitary matrix diagonalizing the mass matrix and $e^{i\varphi k}$ are the Majorana phases.
A convenient parametrization of $\mathcal{M}$ is given by

$$\mathcal{M} = g_A^2 M_{0\nu} = g_A^2 \left(M_{0\nu}^{\mathrm{GT}} - \left(\frac{g_V}{g_A} \right)^2 M_{0\nu}^{\mathrm{F}} + M_{0\nu}^{\mathrm{T}} \right),$$

where $M_{0\nu}^{\mathrm{GT/F/T}}$ are the Gamov-Teller (GT), Fermi (F), and tensor (T) terms.

While precise integrals of the phase space $G_{0\nu}$ are nowadays accurate and less approximate than a decade ago, the plethora of approaches adopted to compute NMEs have generally produced an improvements in the relative errors of the corresponding results while maintaining a significant – although lately reduced – spread among them, which makes them often conflicting with each other. The discrepancy in the calculation for known and testable processes such as single beta decay, electron capture, and $2\nu\beta\beta$ have shown clear disagreements which suggest to take cautious and conservative assessments for $0\nu\beta\beta$ NMEs results.

The size of the axial coupling in the above formula is also not precisely understood yet. While it could be modified to accommodate the discrepancies between NME calculations and experimental results, a decrease of 10% in the value of g_A would imply an increase in data taking time by more than a factor 2 to maintain the same sensitivity. Missing new insight on the subject, which could be given by new experimental investigations such as the one proposed at LNS in Italy, one cannot regard g_A as a reliable quantity. It turns out that this is currently the largest source of uncertainty in the derivation of neutrino mass properties from $0\nu\beta\beta$ results.

Experiments

The experimental panorama is vast. While more than thirty among current experiments, proposal for future experiments, and R&D projects have published papers in the last year,there are few rather clear mainstreams emerging:

- arrays of calorimeters with excellent energy resolution and improved background suppression methods (e.g. GERDA, MAJORANA) or based on unconventional techniques (e.g. CUORE, CUPID)
- detectors with generally poor energy resolution but with topology reconstruction (e.g. EXO, SuperNEMO)
- experiments based on suitable modifications of an existing setup aiming at a different search (e.g. SNO+, KAMLAND)

The fundamental choice for any of these setups is the isotope on which the measurement is based. Depending on it is the relevance of the irreducible background consisting in $2\nu\beta\beta$ decays, which, because of the finite energy resolution of the detector, can provide events with an energy that overlaps with the peak from $0\nu\beta\beta$ decays.

It is clear that the way to boost current experiments is to go up in size, keeping close to zero background via minimum radioactive contamination from detector components (radio-pure materials) and optimal discrimination of residual pulses. The technology is being defined now, and the criteria to define the future detector can be spelled as:

- the best possible energy resolution and excellent time resolution, giving the maximum information on the deposited energy and event topology;
- a reliable and easy to operate detector technology, suitable for long time underground data taking with minimum maintenance;
- a mass of not less than $\mathcal{O}(1\,\mathrm{t})$, possibly isotopically enriched

The experimental activities at DPhP that can clarify the neutrino puzzle within the SM and beyond presently go from high energy physics (LHC) to long baseline experiments (T2K) and to cosmological constraints (BOSS/SDSS et al.). Addressing also $0\nu\beta\beta$ will make it a comprehensive survey. An effort at the DPhP is already ongoing, particularly focused to have a significant impact on the choice of the future $\mathcal{O}(1\,\mathrm{t})$ experiment. It is based on existing expertise on bolometers, which is among the mainstream technologies foreseen for the short future, and it consists of and R&D of crystals based on different isotopes (^{130}Te, ^{100}Mo, ^{116}Cd, ^{82}Se) with the target of building a demonstrator. Parallel efforts to reduce the uncertainty on the axial coupling are also ongoing at DPhP, via the study of the beta spectrum of highly suppressed transitions in ^{113}Cd and ^{115}In.

It has to be noted that within Irfu, contribution to additional experiments come from DPhN (PandaX) and DeDiP (long standing proposal for a pressurized Xe in a metallic sphere).

Future prospects are to define the isotope and technology for the next generation $\mathcal{O}(1\,\mathrm{t})$ experiment around 2020 and start building the detector right after, with a likely option to pass through an intermediate step at $\approx 1/5$ of the final size ($\approx$ 2025) before becoming fully operational with the ultimate setup ($\approx$ 2030).
Recent phenomenological works have addressed the probability of detecting a 3σ $0\nu\beta\beta$ decay signal assuming that neutrinos are truly Majorana particles. The analyses consider current uncertainties on NMEs and g_A, adds cosmological constraints, and look at the different hierarchy scenarios. They conclude that for inverted hierarchy chances are greater than $\approx 50\%$ for the next generation experiments to detect a signal within the first few months from the data taking start (nowadays a fashionable feature). In the more challenging normal hierarchy scenario, favoured by the current indications from oscillation experiments or cosmological observations, the current likelihood to detect a signal within 5 years of live time is greater than 50% for the most promising technology (bolometers) and the experiments will in any case probe a significant amount of the parameter space.

The report writer will provide a document with full bibliographic references by Monday, and apologises for the untimely sending of the present one.