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Neutrinoless double beta decay search with XENON1T and XENONnT

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Summary. — The primary goal of the XENON experiment consists in finding the first direct evidence for the existence of Dark Matter in the Universe via its scattering with xenon target nuclei in a dual-phase time projection chamber detector. The unprecedented low level of background reached demonstrated this detector technology to be suitable also for other exciting rare-events searches among which the neutrinoless double beta decay of ^{136}Xe. The discovery of such a process will shed light on another fundamental challenge in physics nowadays about the nature of neutrinos. In this proceeding I will discuss the current status of neutrinoless double beta decay of ^{136}Xe search in XENON1T. In the context of the advancement of the XENON program, XENONnT is currently collecting its first scientific data in the underground INFN Laboratori Nazionali del Gran Sasso in Italy. With its target mass of 5.9 tonnes of liquid xenon and designed with a high level of background reduction, the XENONnT experiment aims to increase the predecessor sensitivity in rare-events searches. In this proceeding I will also report on the ongoing sensitivity projection studies for neutrinoless double beta decay search in XENONnT.

1. – Introduction

The XENON Collaboration has developed experiments primarily devoted to the search for Weakly Interacting Massive Particles (WIMPs) Dark Matter (DM) candidates through the observation of the possible scattering of a WIMP off xenon nuclei. Over the years, dual-phase liquid xenon time projection chambers proved to be the best technology for WIMPs direct detection [1]. With the improvement of the background reduction and the increase of the target mass from XENON10 to XENONnT, these experiments start to be sensitive to other rare events physics channels on a wide energy range spanning from few keV to MeV [2-4]. Among them, the search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe is of particular interest, since it can shed light on the nature of neutrinos.

The two-neutrino double beta decay ($2\nu\beta\beta$) is a rare nuclear process firstly suggested by M. Goeppert-Mayer in 1935 [7]. It is allowed in the Standard Model (SM) and it has been already observed in several isotopes. Its Feynman diagram is presented in

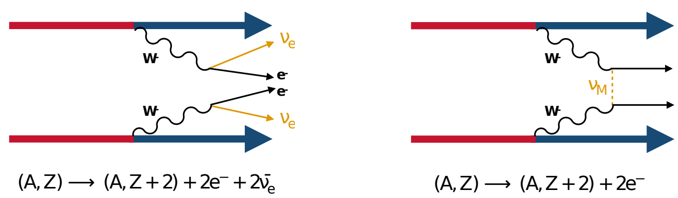

Fig. 1. – Feynman diagrams of $2\nu\beta\beta$ decay (left) and $0\nu\beta\beta$ decay for light Majorana neutrino exchange mechanism (right).

the left part of fig. 1. The right part of the same figure shows the basic mechanism of $0\nu\beta\beta$ decay induced by the exchange of a light Majorana neutrino. This process, theorised for the first time by W. Furry in 1939 [8], would lead to the violation of the lepton number and it is thus forbidden in the SM, indicating that neutrinos are Majorana fermions, *i.e.*, their own anti-particles. The ^{136}Xe is one of the most studied isotope in the quest for the $0\nu\beta\beta$ decay. Its natural abundance in the target of the XENON1T detector has been measured to be around 8.9%. This isotope has already been used to search for $2\nu\beta\beta$ decays by the EXO200 Collaboration that measured a half-life of $(2.165 \pm 0.016^{(stat)} \pm 0.059^{(sys)}) \times 10^{21}$ years with a Q value of (2457.83 ± 0.37) keV [9, 10]. With a ^{136}Xe half-life of $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ years, KamLAND-Zen holds at present the best limit on the $0\nu\beta\beta$ decay search [11].

In this proceeding I will firstly introduce the working principle of the XENON experiments in sect. **2**. The signal and backgrounds models considered for $0\nu\beta\beta$ decay search will be presented in sect. **3** and sect. **4** will cover the development of the $0\nu\beta\beta$ decay data analysis for XENON1T and the sensitivity projection study for XENONnT. I will finally summarize the work discussed in this contribution in the final sect. **5**.

2. – The XENON project: Dual-phase Xe TPCs

The XENON program consists in conceiving and operating increasingly sensitive detectors aiming at finding a first evidence of the existence of dark matter via direct detection. The project started with the XENON10 experiment [13] and continued with XENON100 [14] followed by XENON1T [15]. At present, the forth generation experiment, XENONnT, just started to collect data. All those experiments were and are located at the INFN - Laboratori Nazionali del Gran Sasso (LNGS), an underground laboratory in Italy, which is 3600 meters water equivalent deep. Such a depth allows to reduce the muon flux by a factor of 10^6 with respect to the surface. The XENON project experiments are based on the same detection technology consisting of a dual-phase Time Projection Chamber (TPC) filled with Liquid (LXe) and Gaseous Xenon (GXe), the XENONnT TPC is shown in fig. 2 on the right. Xenon represents an ideal target for WIMP searches because it allows for a self-shielding from external backgrounds thanks to its high stopping power for gamma and beta radiations. Furthermore the low contamination of long-lived radioactive isotopes permits to minimize the sources of internal backgrounds.

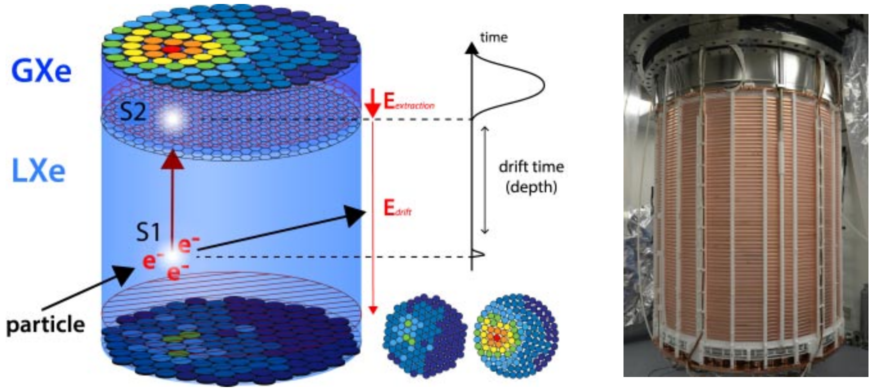

Fig. 2. – (Left) working principle of a dual-phase TPC. (Right) picture of the XENONnT TPC.

A sketch of the working principle of this type of detectors is shown in fig. 2 on the left and can be summarized as follows: when a particle interacts with the detector target, it can either generate a nuclear (NR) or an electronic recoil (ER) depending on the nature of the particle. In particular WIMPs, neutrons or neutrinos may scatter off LXe nuclei undergoing NR, while γ rays, charged particles and neutrinos interact with the atomic electrons producing an ER. The recoil will excite and ionize encountered LXe atoms, causing the release of photons and electrons. Photomultiplier tubes (PMTs) are placed at the top and at the bottom of the TPC to detect the first scintillation signal (called S1) generated by photons, and the second scintillation signal, called S2, produced by ionized electrons following an applied electric field and drifting toward the gaseous phase. The S2 hit pattern from the top PMT array is used to extract the (x,y) coordinates of the interaction, while the z coordinate is inferred from the drift time between S1 and S2: each event is thus reconstructed in three dimensions. The S1/S2 ratio is used to distinguish between NR and ER. This information is fundamental to separate the expected WIMP signals (NR) from the main source of background (ER).

3. – Signal and Background models

The electron penetration length in LXe is $\mathcal{O}(mm)$: this results in a Single Site (or Single Scatter, SS) expected signal topology for $0\nu\beta\beta$ decay, whose energy $Q_{\beta\beta}$ is given by the sum of the two emitted electrons. On the other hands, Bremsstrahlung photons and β-electrons might generate multiple energy depositions giving rise to Multiple Site (or Multi Scatter, MS) topology events. As it will be presented in the following, both internal and external background can mimic the $0\nu\beta\beta$ decay signature in our detector. Using Monte-Carlo (MC) simulations and after having removed MS events, accounted for energy resolution and selected events within an optimized Fiducial Volume (FV), it was possible to prove that the energy of the expected signal follows a gaussian distribution centered at the Q value of the process (*i.e.*, at $Q_{\beta\beta}$).

Two different type of background sources can mimic the $0\nu\beta\beta$ decay signature in our detector: the external and the internal ones.

3·1. *External Backgrounds*. – The decays of the long-lived radionuclides present in detector materials and emanating into the target, introduce a non negligible source of background to the $0\nu\beta\beta$ search. Despite being carefully chosen based on their radiopurity and even with the dedicated screening campaign [16], materials represent the major source of background in the energy ROI. Indeed, the natural decay chains of ^{238}U, ^{235}U and ^{232}Th might introduce ER background in the form of γ-rays that can produce low energy Compton scatters. Precisely, the ^{238}U and ^{232}Th daughters, namely ^{214}Bi and ^{208}Tl respectively, emit γ lines at 2447.9 keV and 2614.5 keV that are close to the $Q_{\beta\beta}$. Their interactions in LXe can thus mimic the signature of a $0\nu\beta\beta$ decay.

3·2. *Internal Backgrounds.* – Internal backgrounds either arise from the interaction between cosmogenic particles and the xenon target or originate from the isotopes present in the noble gas. Among them, the dominant one in the energy Region of Interest (ROI) for the $0\nu\beta\beta$ search is represented by the ^{222}Rn. Radon emanates from the detector materials and induces an intrinsic contribution into the LXe target that originates from the ^{238}U primordial decay chain, in addition to the one from materials. Due to the peculiar topology of ^{214}Bi β-decays into ^{214}Po quickly followed by an α emission of ^{214}Po decaying into ^{210}Pb, we can identify and thus reject this type of events occurring within the instrumented detector, using the so called BiPo tagging technique. This technique can reach a rejection power larger than 99.8% [6]. However, when the decays happen outside the active volume, in the non-instrumented LXe, the BiPo tagging cannot be applied, resulting in a 2.45 MeV γ emission from the ^{214}Bi decay within the FV that will constitute a non negligible source of background.

The second most relevant internal background within the ROI for $0\nu\beta\beta$ decay search is represented by the β-decay of ^{137}Xe. With a Q value at 4.17 MeV far beyond the $Q_{\beta\beta}$, ^{137}Xe is a relevant source of ER background. It is produced through neutron capture on ^{136}Xe occurring either within the TPC itself or in the non-shielded parts (placed outside the water tank) of the purification systems. The muon-induced neutrons produced in the LXe are the principle responsible for the production of ^{137}Xe in the TPC, while the thermal neutrons flux induced by radiogenic decays from the rocks, concrete and materials has the stronger impact on the production of ^{137}Xe in the purification system.

^{8}B solar neutrinos are an irreducible source of background that can be problematic in the energy ROI if the incident neutrino flux and energy are sufficiently high.

Finally, the continuous energy spectrum of the $2\nu\beta\beta$ of ^{136}Xe, with the endpoint at the $Q_{\beta\beta}$, is also a background to the $0\nu\beta\beta$ decay search. Theoretical calculations from J. Kotila and F. Iachello [12] were used in order to model this background. Thanks to the sub-percent energy resolution at $Q_{\beta\beta}$ demonstrated in XENON1T [5], its contribution in the $\pm 1\sigma$ ROI is negligible with respect to the dominant backgrounds in both XENON1T and XENONnT.

4. – $0\nu\beta\beta$ decay search in XENON1T and XENONnT

The primary goal of the XENON experiments is the search for WIMPs. Since the energy issued from the collision between those dark matter candidates and the xenon target is expected to be of the order of ten of keV, those detectors have been optimised to work in this low energy regime. In order to be able to perform a search for $0\nu\beta\beta$ decay of ^{136}Xe in the MeV energy region, several improvements to correctly reconstruct the expected signals are needed. In particular, at energies above $\sim$100 keV, the signals measured by the PMTs start to saturate impacting the energy reconstruction. In XENON1T the above mentioned improvements allowed to reach the world leading energy resolution of $\sim$0.8% (σ/E) at the $Q_{\beta\beta}$ of ^{136}Xe in a LXe dual phase TPC [5]. Based on this promising result, a blinded analysis on XENON1T data to search for the $0\nu\beta\beta$ decay is currently ongoing. In XENON detectors, the expected $0\nu\beta\beta$ decay signal is a Single Site ER interaction (see sect. **3**). In order to maximize the signal acceptance while rejecting potential background events, different selection criteria based on data quality checks, signals properties and reconstructions have been used. Among them, the selection of events within a FV is a key element to increase the experimental sensitivity. The FV depends on the target mass and the background rate in the volume and has been optimized to increase the signal over background ratio. In parallel to the XENON1T analysis, a sensitivity projection study for $0\nu\beta\beta$ decay search in XENONnT is currently being performed. Thanks to a larger LXe active mass (x3) and a significant foreseen background reduction (x1/10), the sensitivity of XENONnT for $0\nu\beta\beta$ decay search is expected to significantly increase with respect to its predecessor.

5. – Summary

With its results, the XENON project has proven the excellent capabilities of dual phase liquid xenon Time Projection Chambers in searching for rare events on a broad energy range from keV to MeV. Among the most interesting search that is possible to perform with such a technology, there is the search for neutrinoless double beta decay. This process is of fundamental interest since its discovery will shed light on the nature of this elusive particle. In this proceeding I presented the current status in XENON1T and future perspectives in XENONnT of $0\nu\beta\beta$ decay of ^{136}Xe search. Although LXe dual phase TPCs are currently not competitive with $0\nu\beta\beta$ dedicated experiments, it has been shown that this technology can be used for a simultaneous search of dark matter and neutrinoless double beta decay. Among other searches, this is what the previous and current XENON experiments are used for.

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