IL NUOVO CIMENTO **46 C** (2023) 115
DOI 10.1393/ncc/i2023-23115-9

Communications: SIF Congress 2022

Calibration of XENON1T with ^{37}Ar diffused inside the detector

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received 27 January 2023

Summary. — The XENON project, located at INFN Laboratori Nazionali del Gran Sasso, aims to directly detect dark matter particles, through the interaction with xenon atoms inside a dual-phase Time Projection Chamber. At the end of the last XENON1T science run, in 2018, a low-energy calibration with an internal ^{37}Ar source was performed for the first time. ^{37}Ar decays by electron capture, with 35-days half-life, emitting photons and electrons which generate two mono-energetic signals, at 2.82 keV (K-shell) and 0.27 keV (L-shell). The final results of the calibration confirm that the behaviour of the detector is well-understood. Additionally, it was proven that cryogenic distillation efficiently removed ^{37}Ar and, therefore, this source can be used for calibrations in multi-tonne xenon detectors.

1. – Introduction

The XENON1T experiment, located underground in the INFN Laboratori Nazionali del Gran Sasso (Italy), was designed for the direct detection of dark matter (DM) particles, primarily in the form of weakly interacting massive particles (WIMPs), via elastic scattering off xenon nuclei [1]. The detector was a dual-phase time projection chamber (TPC), with a height of 97 cm and a diameter of 96 cm, it was equipped with 248 photo-multiplier tubes (PMTs), and contained 2 t of liquid xenon (LXe) target.

In LXe TPCs, particles interacting with LXe atoms produce a prompt scintillation signal (S1), from the de-excitation of excited molecular states, and ionization electrons. Electrons are drifted by an electric field to the top of the detector, where they get extracted from liquid into gas phase, producing proportional scintillation light (S2) via electro-luminescence. Both signals are observed by arrays of PMTs at the top and bottom of the TPC. From S1 and S2, the energy deposited and the three-dimensional position of interactions can be reconstructed [2]. The position is evaluated using the time difference between S1 and S2 (depth of interaction z) and the light distribution pattern in the top PMTs array (horizontal coordinates x, y and radius r). Background from radioactivity in detector materials is then suppressed by selecting a fiducial region in the active volume.

The ratio between S2 and S1 allows discriminating electronic recoils (ERs), induced by β particles, γ rays and neutrinos scattering off electrons, from nuclear recoils (NRs), induced by neutrons or neutrino scattering off nuclei [2]. WIMPs are supposed to produce NRs, but, in principle, ERs could be induced by alternative DM candidates. Recently, the capability of reaching extremely low background, even for ERs, gave a boost to investigations of these interactions for physics beyond the Standard Model, especially at low energies ($\sim$ keV) [3]. For this reason, a calibration of low-energy ER with mono-energetic sources acquires particular importance.

2. – Source description

^{37}Ar isotope decays by electron capture into ^{37}Cl with half-life of 35.01 days, followed by an emission of x-rays and Auger-Meitner electrons. The energy deposit corresponds to the binding energy of the captured electron and results in lines at 2.82 keV, 0.27 keV and 0.01 keV, with a branching ratio of 90.2%, 8.7% and 1.1%, respectively [4]. The K- and L-shell lines allow studying the low-energy detector response, since they are close to the 1 keV energy threshold of XENON1T and below the 9 keV peak of the isotope $^{83\mathrm{m}}$Kr, usually employed to study spatial response of the detector.

The calibration with ^{37}Ar was performed for the first time in XENON1T at the end of the last science run in 2018 [5]. The ^{37}Ar source was contained in a quartz ampule, where an ultra-pure sample of ^{36}Ar was irradiated with thermal neutrons at the TRIGA Mark II reactor of the University of Mainz. A dosing system was used to open the ampule and inject the desired activity into the LXe, exploiting an arrangement of well-known volumes that dilutes a small portion of the initial activity with xenon. Since a half-life of 35.01 days would not be compatible with the timescale of a DM detector, the ^{37}Ar active removal was required. Since argon has a higher volatility with respect to xenon, it was possible to effectively remove it via online cryogenic distillation, reaching previous background level conditions after 24 days.

3. – S1-S2 analysis

For the analysis of ^{37}Ar K-shell at 2.82 keV, events with both signals S1 and S2 are considered and the standard quality cuts used for science data are applied. The S1 and S2 signals are corrected (cS1 and cS2) for position-dependent effects, including light collection efficiency. Additionally, S2 is corrected for the absorption of electrons by electro-negative impurities, which is a function of the drift time [2].

One of the main goals of this study is the determination of the light (L_y) and charge yield (Q_y), *i.e.*, the average signals detected per unit of energy, at 2.82 keV. These values are evaluated by performing a fit of the signal spectrum in the S1-S2 space. The distribution for a mono-energetic source is usually assumed as a two-dimensional Gaussian, but, at low energy, other effects must be considered. In fact, for S1 signals, with $O(10)$ detected photons, the spectrum follows a Poisson distribution, the PMT single-PE response is not Gaussian, and PMTs have double-PE emission with a binomial process. It was found that a skew Gaussian distribution describes these effects, but also the position-dependent impact on cS1 of S1 detection efficiency (which drops quickly for S1 $\lesssim$ 5 PE), must be considered. The LXe TPC is divided into r-z bins of equal volume, and, for each of them, a two dimensional fit in uncorrected S1 and corrected S2 space. The results of the fit are shown for two different spatial bins, taken as examples, in fig. 1.

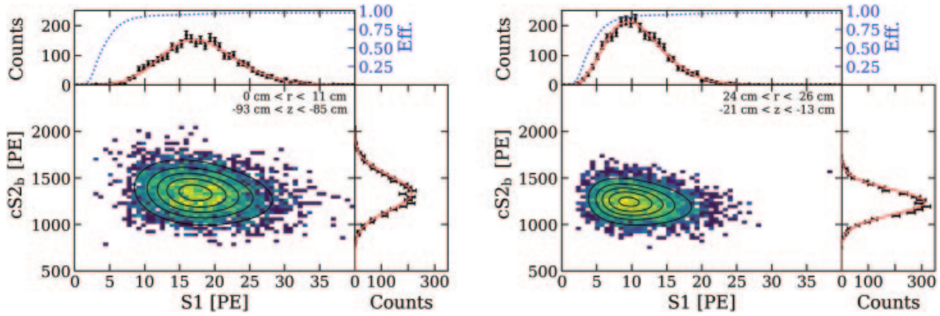

Fig. 1. – Examples of event distribution for two r-z bins at top and bottom of the TPC in S1-cS2$_{\mathrm{b}}$ space, where cS2$_{\mathrm{b}}$ indicates the signal detected on the bottom PMT array (figures from [5]). In the top and right panels, the projection of the signals are reported; the black points indicate data, while the red line shows the fit. The dotted blue line represents the S1 detection efficiency.

The mean S1 and S2 values in each bin are scaled by the known light collection efficiency and averaged to get the overall yields $L_y = (4.66 \pm 0.01_{\mathrm{stat.}})$ PE/keV and $Q_y = (452.4 \pm 0.1_{\mathrm{stat.}})$ PE/keV, which can be converted into (32.3 ± 0.3) photons/keV and (40.6 ± 0.5) electrons/keV, for XENON1T drift field (82 V/cm). The obtained results, compared with other calibration sources at higher energy (see fig. 2, left panel), show a linear energy response for a wide range, down to 2.82 keV. Two detector constants (g_1 and g_2) are evaluated from the yields, and are used to reconstruct the deposited energy for any event, by the relationship $E = 13.7 \cdot (\mathrm{cS1}/g_1 + \mathrm{cS2}/g_2)\,\mathrm{eV}$ [2]. With this additional information, the reconstructed energy spectrum of ^{37}Ar K-shell signals is estimated. It is described, as expected from S1 distribution, by a skew Gaussian with mean at (2.83 ± 0.02) keV, consistent with the literature value.

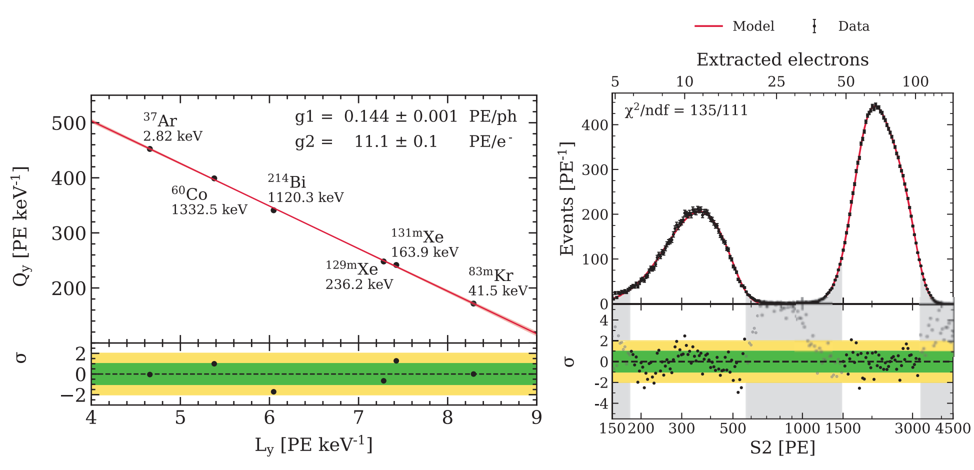

Fig. 2. – Left panel: Charge- *vs.* light-yield for various mono-energetic sources (black points). The linear fit (red line) allows estimating the detector-dependent constant $g1$ and $g2$. Right panel: Best-fit model of S2 spectrum compared with data. The gray-shaded regions are excluded from the fit, performed in the central 95% region of the two peaks. Figures from [5].

4. – S2-only analysis

S1s produced by ^{37}Ar L-shell decays, at 0.27 keV, are below the energy threshold, which depends on the 3-fold PMTs coincidence used to reconstruct events. Hence, basically no event with S1-S2 is visible at 0.27 keV. Nonetheless, S2s are still detectable and it is possible to study the detector response at L-shell energy, by performing an S2-only analysis. In this approach, where S1 is not required, the energy threshold is lower, but, since the depth of interaction cannot be determined using the drift time, it results in worse fiducialization and weaker background rejection, requiring a dedicated set of quality cuts.

Even if S2 cannot be corrected for position effects, a parametric model, describing the response of the detector for the ^{37}Ar energy deposition in the (S2, z) space, is built. Both L-shell and K-shell signals are generated to compare the distributions in the two regions. The model probability distribution, which allows evaluating the event rate, includes the electrons production for a given energy deposit, the survival probability, and the PMTs signal production. The model, which takes the rate and the charge yield of the two peaks as free parameters, is fit to the data in the uncorrected S2 space, with the binned maximum likelihood method. The results are shown in fig. 2 (right panel). The agreement between model and data is good for both L-shell and K-shell. In particular, the measured event ratio between the two peaks is $(10.11 \pm 0.44)\%$, that is within 1Σ from the expected value of 9.67%. This indicates that the S2 detection efficiency and cuts acceptance in the energy range between 0.27 keV and 2.82 keV are well understood. From the best fit, the estimated charge yield at 0.27 keV, for XENON1T drift field, is $68.0^{+6.3}_{-3.7}$ electrons/keV.

5. – Conclusions

Two analyses of the ^{37}Ar XENON1T calibration data have been performed, to evaluate the detector response close to the detector threshold. A good agreement with simulations and other measurements in the same energy range has been found [5]. The reconstructed energy of the K-shell is in agreement with the expected value, showing linearity of the response down to ∼keV energies. The S2-only analysis validates the detector efficiency and provides results in an energy region where only a few measurements are available. Furthermore, the removal of this source after calibration via cryogenic distillation proves that ^{37}Ar can be used as a regular calibration source for multi-tonne xenon detectors.

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