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Study of background from tritium and ^{37}Ar decays in LZ using Monte Carlo simulations

Tomas Sousa[1,a]

[1] *Sorbonne University, Paris, France*

Project supervisor: E. Asamar

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Abstract. This document presents the results of my study conducted as part of the 2020 Summer Internship Programme at LIP (Laboratory of Instrumentation and Experimental Particle Physics), in Coimbra (Portugal). The purpose of this work is to do a first study of the potential background from tritium and ^{37}Ar decays for the future LZ (LUX-ZEPLIN) experiment, considering the recent excess reported by XENON1T.

KEYWORDS: DARK MATTER, DIRECT DETECTION, WIMP, LUX-ZEPLIN, XENON1T, ARGON, TRITIUM

1 Introduction

1.1 Dark Matter

Several astronomical observations based on gravitational effects indicate that 85% of the total matter content of the universe does not emit or absorb electromagnetic radiation. This contribution is called dark matter. The existence of dark matter poses a problem for the current fundamental theory of particle physics, namely the Standard Model (SM), because it cannot be explained in terms of known elementary particles. Therefore, the existence of dark matter is considered as one of the most important empirical evidences of physics beyond the SM.

1.2 WIMPs

The available evidences of dark matter do not constrain neither the mass of its elementary constituents, nor the strength of its interaction with ordinary matter (if any). For this reason, several dark matter hypotheses exist. One hypothesis of particular interest is the weakly-interacting massive particle (WIMP) paradigm, that assumes particles of 10 to 100 keV, that couple to ordinary matter via the weak interaction. This hypothesis is able to explain the observed amount of dark matter in the universe.

1.3 Direct Detection Experiments

Currently, several experiments are attempting to measure the elementary constituents of dark matter. In particular, direct detection experiments aim to detect WIMPs that might populate the vicinity of Earth, by measuring recoiling nuclei from their interaction with a target of ordinary mass. Direct detection experiments are also sensitive to particles in the keV and MeV range, and therefore environmental radiation from radioactivity or cosmic rays represent a background for these searches.

[a] e-mail: tomas.sousa@etu.sorbonne-universite.fr

2 The LZ Experiment

LUX-ZEPLIN (LZ) is a second-generation dark matter direct detection experiment that will operate around 1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA. Using a two-phase xenon detector with an active mass of 7 tonnes, LZ will search primarily for low-energy interactions with WIMPs [1].

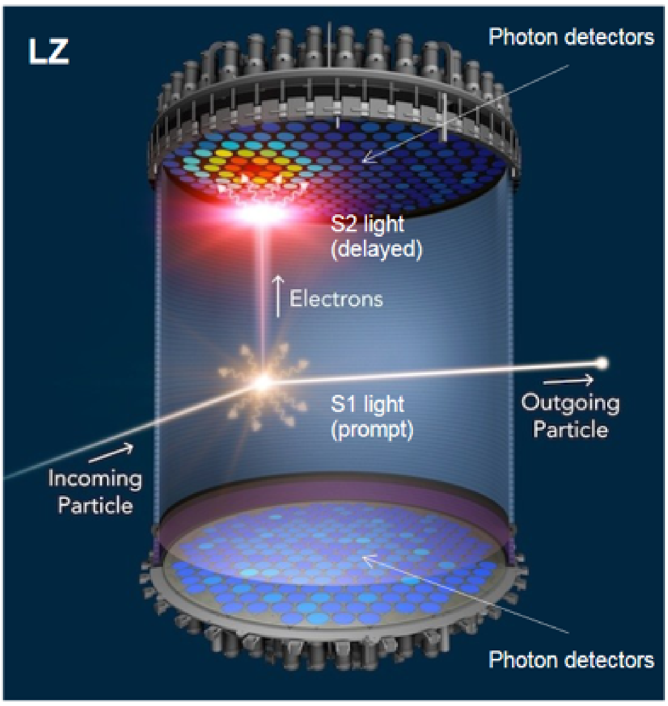

Figure 1. Schematic representation of the detection process in the LZ experiment.

The interaction between a WIMP and the liquid xenon generates scintillation photons (S1 in Figure 1), and releases ionization electrons. The electrons drift upwards due to an applied electric field, and are extracted to the gas layer of the Xenon, where they generate electroluminescence photons (S2 in Figure 1). We can then measure S1, S2, and their delays with the photo-multiplier arrays.

In order to achieve the desired sensitivity to WIMPs, LZ has carried out an extensive program to control the backgrounds of the experiment. In this context, the recent results from XENON1T (section 3), have motivated the study of the background from tritium and ^{37}Ar decays in LZ, that might be present in very small amounts, and affect the low-energy range of electron recoils.

3 The XENON1T excess

A similar experiment based on a double-phase xenon detector, XENON1T has recently observed an excess of electron recoil events at low energies, namely below 5 keV, above the rate of expected background events [2].

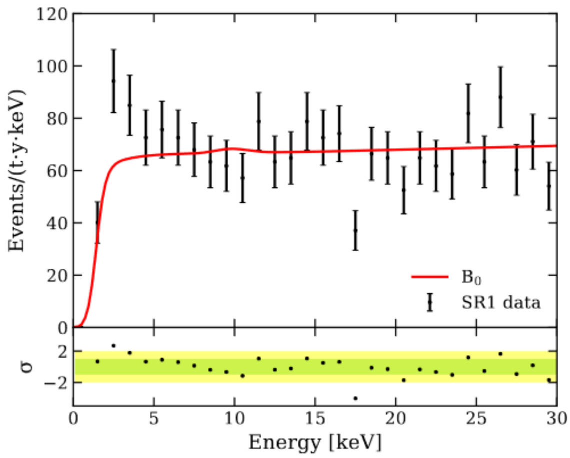

Figure 2. SR1 data from XENON1T, taken from [2]. There is an excess in low energies of the measured data compared to the background model (B0). The authors mention that "Within 1–7 keV, there are 285 events observed in the data compared to an expected 232±15 events from the background-only fit".

The XENON1T Collaboration proposes three hypotheses to explain the excess. Two of them involve new physics, while the third considers a known background, namely the beta decay of tritium, that has a continuous energy spectrum that extends up to 18.6 keV. Another potential background that could explain this excess, not considered in the XENON1T paper[2] is the X-ray emission following the electron capture (EC) of ^{37}Ar, that occurs at 2.6 keV. Given the similarity between the two experiments, it is important to study these two backgrounds, since they could be possible sources in LZ as well.

4 Simulations

Monte Carlo modelling of events for LZ serves two main purposes: 1) to support the design of the detector through the assessment of background rates, with input from radioactivity measurements; and 2) the prediction of the sensitivity of the experiment to various rare event searches.

The tool used to perform these simulations is BACCARAT (Basically A Component-Centric Analog Response to AnyThing), that is an in-house software package that brings a useful interface for Geant4 for low-background experiments. Central to this interface is the shift of focus towards individual volumes in the geometry (components) [3]. Geant4 is a widely used simulation toolkit, devoted to simulate the interaction of radiation with matter. In addition to particle physics, it also has applications in medical physics, nuclear engineering and astronautics. It requires to specify: 1) the geometry and materials of the experimental setup; and 2) the physics models that describe the radiation-matter interaction.

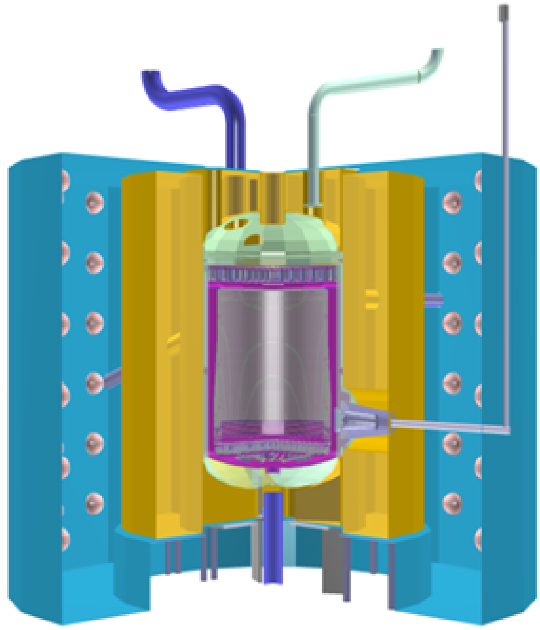

Figure 3. Visualization of the detector in BACCARAT. Figure from [3].

5 Results

We simulated 10000 events for the beta decay of tritium and another 10000 for the EC of ^{37}Ar, using BACCARAT. After that, we normalized the counts, assuming that the levels of ^{37}Ar and tritium are those that would explain the totality of the XENON1T excess [2]. Finally, we added the contribution from the rest of the backgrounds, that is approximated as a flat spectrum [1], and smeared the resulting spectrum by the energy resolution function measured by XENON1T.

On the ^{37}Ar spectrum (Figure 4), the well-defined peak is due to the X-ray photon which is emitted with a discrete energy, whereas on the tritium spectrum (Figure 5) the beta decay produces one electron (which is detected) and one neutrino (which is not detected). The measured energy is that of the electron, which will have a distribution between 0 and the maximum value (around 18 keV).

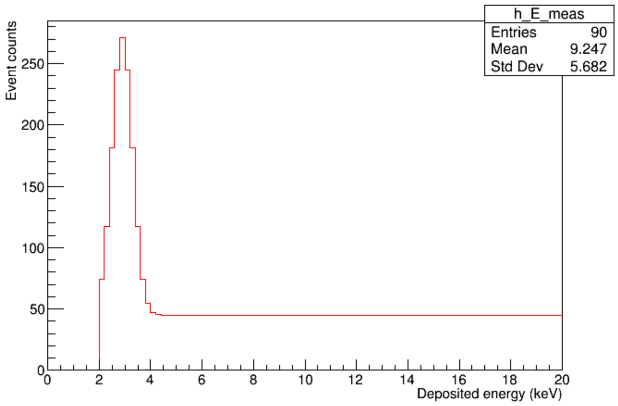

Figure 4. The generated spectrum for ^{37}Ar. There is a peak between 2 and 4 keV. The straight line on the right part is from the linear approximation of the background, mentioned in section 5.

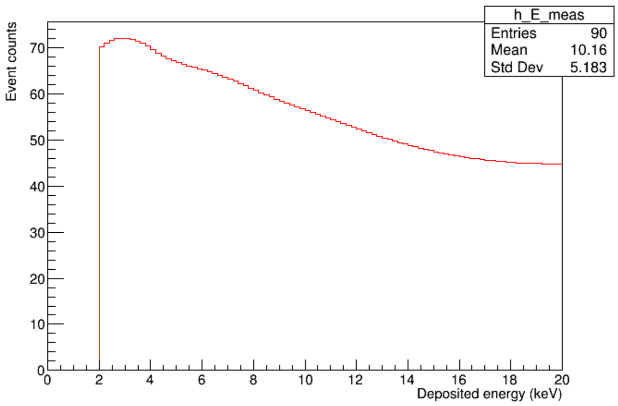

Figure 5. The generated spectrum for Tritium. There is a significant background at low energies, but it is not as much as the ^{37}Ar spectrum (see y axis scale), and it encompasses a broader band (up to approximately 18 keV).

6 Conclusion

We simulated, using BACCARAT, the expected background for the decay of ^{37}Ar and tritium, assuming, in each case, the same contamination levels that would explain the totality of the XENON1T excess. This study is important because it gives, for the first time, a prediction for these backgrounds in LZ, that, in view of the XENON1T results, might be relevant for searches using low-energy data. Besides, the similarity between the spectrum for ^{37}Ar and the XENON1T spectrum seems to support the hypothesis that the decay of this isotope could be the cause of the excess observed in the latter case.

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References

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