Background studies

for a ton-scale argon dark matter detector (ArDM)*

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The ArDM project aims at operating a large noble liquid detector to search for direct evidence of Weakly Interacting Massive Particles (WIMP) as Dark Matter in the universe. Background sources relevant to ton-scale liquid and gaseous argon detectors, such as neutrons from detector components, muon-induced neutrons and neutrons caused by radioactivity of rock, as well as the internal $^{39}$Ar background, are studied with simulations. These background radiations are addressed with the design of an appropriate shielding as well as with different background rejection potentialities. Among them the project relies on event topology recognition, event localization, density ionization discrimination and pulse shape discrimination. Background rates, energy spectra, characteristics of the background-induced nuclear recoils in liquid argon, as well as the shielding performance and rejection performance of the detector are described.

1. Introduction

Astronomical observations suggest that over 80% of the matter contained in the universe is Dark Matter, which presumably consists of unknown and invisible WIMPs (Weakly Interacting Massive Particles). The most common candidate is the lightest supersymmetric particle. Direct detection experiments aim at measuring elastic scattering of WIMPs with nuclei. The energy transferred to the nuclei is typically below 100 keV. Due to this low energy range and the small cross section, such a signal is difficult to measure and signal sensitivity is limited by ordinary backgrounds. Background radiation arises from several sources and is of different significance. One dominant background source is the contamination with radioactive elements, namely uranium and thorium chains, and potassium-40 resulting in $\alpha$, $\beta$

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and $\gamma$ emissions as well as neutron production processes, of the materials used in and around the detector. Another source of neutron background in underground environments comes from interactions of cosmic muons with matter, resulting in neutron production. A third background source can arise from internal contamination of the target material, e.g. with radioactive isotopes.

The experiment for which the present study has been carried out is ArDM [1–4], a ton-scale liquid argon detector. The technical concept of the experiment relies on the independent readout of ionization charge by LEM and of scintillation light by photo-detectors [4]. This paper summarizes the results of Monte Carlo studies carried out to assess the impact of different background radiation in this project.

2. Neutron background

An important background is neutron-induced nuclear recoils which are hardly distinguishable from WIMP events. The neutrons from radioactivity arise mainly from contaminations of materials or rock by the two radioactive elements uranium and thorium, and their decay-chain daughters. The decay chains of $^{238}$U and $^{232}$Th contain $\alpha$ decays with $\alpha$ energies of 3.5 to 11 MeV. These $\alpha$ undergo $(\alpha,n)$ reactions, thereby producing neutrons with energies in the MeV range. The cross section depends on the material and on the $\alpha$-energy [5]. Typical yields are $10^{-8}$ to $10^{-5}$ neutrons per $\alpha$. Besides $(\alpha,n)$ reactions, neutrons can arise from spontaneous fission. The number of neutrons arising from these two processes is typically of the same order of magnitude, but depends on the material. Muon-induced neutrons arise from cosmic muon interactions with surrounding materials. Highly energetic muons are able to penetrate deep underground. Neutrons are produced by spallation or photonuclear processes, or by secondary interactions of muon-induced hadronic showers. The shielding of the detector optimized for natural radioactivity is less efficient in this case and faster neutrons can penetrate inside the detector fiducial region. Shielding and detector components can also act as a target for muons, however the expected production rates are low.

2.1. Neutrons from radioactivity in detector components

The ArDM detector parts consist mainly of the following materials: stainless steel, vetronite, polyethylene, borosilicate glass, ceramics and copper (see Ref. [4] for details). In general, metallic materials contain much less U/Th...
contamination, i.e. typically a few ppb. Minerals and glasses generally have higher contaminations of the order of a few hundred ppb. We have estimated the number of emitted neutrons using the data from Ref. [5]. Furthermore, the emission numbers have been simulated with SOURCES4a for cross-check. The numbers obtained with the two different approaches agree well. The biggest contribution for standard materials comes from photomultiplier tubes located on the bottom of the detector and large electron multiplier (LEM) plates located on the top of the detector, since these two parts contain glass. Low background versions of these two components should reduce the rate by about two orders of magnitude. The resulting neutron production rates and the precise assumptions for component masses and contaminations are summarized in Table 1.

| Component     | Mass (kg) | ppb U | ppb Th | n/year |
|---------------|-----------|-------|--------|--------|
| Dewar (steel) | 1000      | 0.6   | 0.7    | 380    |
| LEM Vetronite | 2         | 1000  | 1000   | 10000  |
| LEM low bg.   | 4         | <2    | <2     | <40    |
| PMT std. version | 2.4 (80 tubes) | 400  | 400    | 12000  |
| PMT low bg.   | 9.8 (14 tubes) | 30   | 30     | 1400   |
| Pillars       | 13 (8 Pillars) | 20   | 20     | 310    |

2.1.1. Neutron spectra

The energy spectra of neutrons coming from U and Th decay chains have two contributions, namely the one from spontaneous fission and the other from \((\alpha, n)\) reactions. The spontaneous fission spectrum is described by 
\[\frac{dN}{dE} \propto \sqrt{E} \exp(-E/1.29).\] About 2 neutrons are emitted per spontaneous fission. The spectrum of neutrons coming from \((\alpha, n)\) reactions is more involved, since the \((\alpha, n)\) cross section is material-dependent. For the computation of the spectra in detector component materials, the simulation program SOURCES4a was used. The code was extended to \(\alpha\) energies above 6 MeV by [6]. The resulting spectra for stainless steel (dewar) and Vetronite (LEM) are shown in Fig. 1.
2.2. Neutrons from radioactivity in rock and concrete

The minerals constituting the rock overburden in an underground laboratory also contain small amounts of U and Th, causing neutron radiation in the same way as in the detector components. The level of the contamination strongly depends on the location and the elemental composition of the rock. Usually the U/Th contamination is on the order of a few hundred ppb. The studies described here have been carried out for the Canfranc Underground Laboratory. It is located in the Pyrenees at a depth of 2450 m.w.e. A concrete layer covers the walls of the laboratory, which also affects the neutron radiation flux.

CH$_2$ is the typical material used as shield against these ambient neutrons. The number of neutrons coming from rock and concrete and reaching different depths of the shielding was simulated with GEANT-4 [8]. The neutron flux decreases by approximately one order of magnitude after every 10 cm of CH$_2$ at energies up to 6 MeV, for higher energies the suppression is slightly less. The suppression for concrete neutrons is slightly lower, especially for higher energies. On the average, 60 cm of CH$_2$ reduce the flux of neutrons by about six orders of magnitude.

2.3. Detector response to neutrons

Background neutrons interact with the detector via elastic scattering with argon nuclei. The imparted recoil energy on the nucleus caused by a neutron with energy $E_n$ and a scattering angle $\theta$ is $E_R \simeq 2E_n \frac{M_n}{M_n + M_{Ar}} (1 - \cos\theta)$. 
Neutrons from the various sources mentioned above have been simulated with the proper energy spectrum and fully propagated through a detailed geometry of the detector with GEANT-4. As an example, the resulting argon recoil spectrum for neutrons from detector components is shown in Fig. 2.

![Fig. 2. Spectrum of argon recoils caused by neutrons from detector components.](image)

Of the neutrons entering the fiducial volume, more than 50% can be rejected because of multiple scattering, since a WIMP would never scatter more than once within the detector active volume. The number of neutron scatters depends on the size of the fiducial volume, the distance of the neutron emitting components to the fiducial volume and on the energy threshold. Assuming that a WIMP-like event is a single recoil with an energy between 30 keV and 100 keV, approximately 5% of the neutrons from detector components produce WIMP-like events. The number of remaining events per year is 12 for the neutrons from the dewar, 800 for the standard material LEM, below 2 for the low background LEM, 480 for the standard PMTs, 56 for the low background PMTs and 19 for the pillars; to be compared with 3500 WIMP events at $\sigma_{\text{WIMP-nucleon}} = 10^{-7}$ pb.

### 3. $^{39}$Ar electron background

Commercially available Argon is procured by liquefaction of air and contains radioactive isotopes. $^{39}$Ar decays via $\beta$-disintegration into $^{39}$K with a half-life of 269 years and Q=565 keV. The concentration of $^{39}$Ar in atmospheric argon is $(7.9\pm0.3)\cdot10^{-16}$ g/g [7], causing a decay rate of 1 kHz in one ton of argon. $\gamma$s from U/Th of the detector components produce an interaction rate which is about three orders of magnitude smaller.
The rejection of electron and $\gamma$ events is facilitated by two means: charge/light ratio discrimination [1] and pulse shape discrimination [9]. The first uses the fact that the ionization yield of nuclear recoils is highly quenched compared to that of electron/$\gamma$, while the scintillation yield is similar. The pulse shape analysis relies on different populations of the fast and slow components of scintillation. In order to overcome the internal $^{39}$Ar background, a combined rejection power of about $10^8$—depending on the WIMP-nucleon cross section—is required.

4. Conclusion

Three main background sources for the ArDM experiment—a liquid argon ton-scale detector—have been studied. Neutron radiation is the most important background, since neutron events have the same signature inside the detector as WIMP events. The main neutron background comes from contaminations of detector components with radioactive elements. Neutrons from rock and concrete of the underground laboratory can be shielded by a thick enough CH$_2$ shield. The internal $^{39}$Ar background is strongly suppressed if the light/charge ratio and the scintillation light time distribution are measured precisely enough.

References

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