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Studies on the efficiency of the neutron shielding for the SIMPLE dark matter search

A.C. Fernandes [a,b,*], M. Felizardo [c,a], A. Kling [a,b], J.G. Marques [a,b], T. Morlat [b]

[a] Instituto Tecnológico e Nuclear, Unidade de Reactores e Segurança Nuclear, Estrada Nacional 10, 2686-953 Sacavém, Portugal
[b] Centro de Física Nuclear da Universidade de Lisboa, Av. Prof. Gama Pinto, 2, 1649-003 Lisboa, Portugal
[c] Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

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ABSTRACT

The SIMPLE project for direct dark matter search is located in a deep underground laboratory, where non-WIMP signals are expected due to neutrons and alpha particles naturally occurring in the facility. This work presents a first study on the efficiency of the neutron shielding for SIMPLE and possible routes for its optimization. The evaluation of the neutron component considers spontaneous fission and (α,n) neutrons originating from the ^{238}U and ^{232}Th present in the experiment materials. Using recently published data on (α,n) yields and spectra, a Monte Carlo model using the MCNP code is employed to simulate the transport of both spontaneous fission and (α,n) neutrons. The application of MCNP offers an alternative method to the SOURCES code used systematically by others for the evaluation of the (α,n) component. Results supporting the optimization of the neutron shield for SIMPLE are described and the feasibility of reducing the event rate to less than 1 evt/kgd is demonstrated.

1. Introduction

Dark matter search experiments are designed to detect astroparticle dark matter candidates, generically called Weakly Interacting Massive Particles (WIMPs). For direct WIMP detection, less than 1 event per day is expected to occur in 1 kg of detector mass (1 evt/kgd). Although search experiments are performed in deep underground facilities, where the rock overburden shields against the cosmic rays, discrimination of these phenomena against more frequently occurring background signals from the natural radioactivity of the underground site and detector materials requires additional methods for background suppression or rejection.

Superheated Instrument for Massive ParticLe Experiments (SIMPLE), located at the LSBB (Laboratoire Souterrain à Bas Bruit, Pays d'Apt, southern France) underground laboratory [1], is one of many experiments to search for evidence of WIMP interactions. Fluorine-loaded Superheated Droplet Detectors (SDDs) are used, as their intrinsic insensitivity to low Linear Energy Transfer (LET < 150 keV μm^{-1}) particles eliminates a significant part of the potential background events, such as muons, electrons and photons. A general description of the SIMPLE experiment and the latest measurement results can be found in Refs. [2,3], respectively.

Due to the LET detection threshold the main contributions to the background signal of SIMPLE stem from alpha particles (due to environmental radon and radio-impurities in the detector material) and neutrons with energies larger than 8 keV. These are produced in (i) spontaneous fission, mostly from the ^{238}U present in the materials that surround and constitute the detectors; (ii) (α,n) interactions due to natural alpha-emitters such as uranium and thorium; (iii) nuclear reactions induced by cosmic muons. As the latter contribution decreases exponentially with increase in facility depth, it is relatively small in deep underground sites, where the background neutron field is essentially due to the occurrence of U and Th in the materials. Monte Carlo calculations of the neutron background in such experiments have been performed by various authors [4–6]. A review of the various methods used is given in Ref. [7]. General-purpose codes like FLUKA, GEANT and LAHET are applied to simulate the production of muon-induced neutrons, for neutron transport and source propagation (MCNP and MCNPX are also applied for the two latter purposes). The production of (α,n) neutrons is generally dealt with using SOURCES, a code specifically developed for the determination of neutron production rates and spectra from (α,n) reactions, spontaneous fission and delayed neutron emission due to the decay of various radionuclides. SOURCES is often modified in order to extend the upper energy range of the alpha particles under consideration from 6.5 MeV in the original version. Recently published data of energy spectra

* Corresponding author at: Instituto Tecnológico e Nuclear, Unidade de Reactores e Segurança Nuclear, Estrada Nacional 10, 2686-953 Sacavém, Portugal. Tel.: +351 219946152; fax:+351 219941039.
E-mail address: anafer@itn.pt (A.C. Fernandes).

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and production yields of (α,n) neutrons in materials containing ^{238}U, ^{232}Th or ^{nat}Sm [8] offer an alternative to SOURCES and can be incorporated directly in the source term of the general-purpose codes.

In this work the efficiency of the SIMPLE shielding against the neutron contribution (from spontaneous fission and (α,n) reactions) to the background signal of the SIMPLE experiment is evaluated using the MCNP code (version 5) [9]. The results suggest the necessity of additional neutron shielding for the SDDs, which are similarly evaluated in order to obtain event rates smaller than 1 evt/kgd.

2. Geometry and materials

Each SSD consists of a 900 ml glycerin-based gel matrix with a 12–20 g suspension of superheated R-115 liquid (C_2ClF_5), contained in a square glass flask of 12 cm height. The current SIMPLE experiment uses fifteen detectors installed in a water bath inside a $97 \times 130 \times 65$ cm^3 tank. The SDDs are distributed in alternating positions in a 16 cm square lattice and can be raised as much as 50 cm above the tank floor. A water layer of 3 cm above the glycerin level limits the diffusion of atmospheric radon into the detectors; the use of high radiopurity food materials provides an α-contamination level smaller than 0.5 evt/kgd.

The tank is located within a 60 m^3 room at a depth of 1500 mwe (meter water equivalent) within the LSBB. The surrounding rock is calcite. Floor plan dimensions are 400×564 cm^2. The room is equipped with a 1 cm-thick steel lining forming a Faraday cage. The ceiling has a semi-cylindrical shape (diameter 404 cm), the room height varying between 212 and 305 cm. Room walls, ceiling and floor consist of concrete, with a thickness between 30 and 100 cm. The room floor contains several steel-covered, 50 cm deep crawl spaces previously used for cable conduits. The tank sits on a wooden support structure with a 32 cm height above the concrete floor in the central region of the room (the latter is further referred to as the “tank pedestal”).

The current shielding of the experiment consists of 50 cm water in the tank, below the SDDs, and a “castle” of 20 l water boxes $22 \times 25 \times 38$ cm^3 symmetrically installed around and above the tank to produce water thicknesses of 50 and 75 cm, respectively. The tank pedestal is surrounded by an arrangement of water boxes (height 50 × width 50) cm. Some water boxes are slightly deformed due to the weight loading, leading to gaps in the lateral part of the shield.

Fig. 1 presents a schematic view of the room, assuming a uniform concrete thickness. Some structures are removed from the figure for clarity (rock, left concrete wall, front water shield and tank water above and around the detectors). The water shield pieces placed along the room length (left and right in the figure) will be designated as “side shield”, while those facing the room ends (not represented in the figure) will be referred to as “end shield”.

MCNP input requires a description of the facility geometry and materials (elemental composition and density) where neutron transport is simulated. Unless explicitly mentioned, constant concrete and rock thicknesses of 30 cm and 1 m, respectively, were used in the simulations. The ENDF-B6.0 neutron cross-section library, included in the MCNP package, was used to describe neutron interactions with the materials.

The neutron source is defined in terms of energy spectrum and location. As MCNP outputs are given relative to one source neutron, a final scaling to the actual source emission rate is performed in order to obtain absolute results.

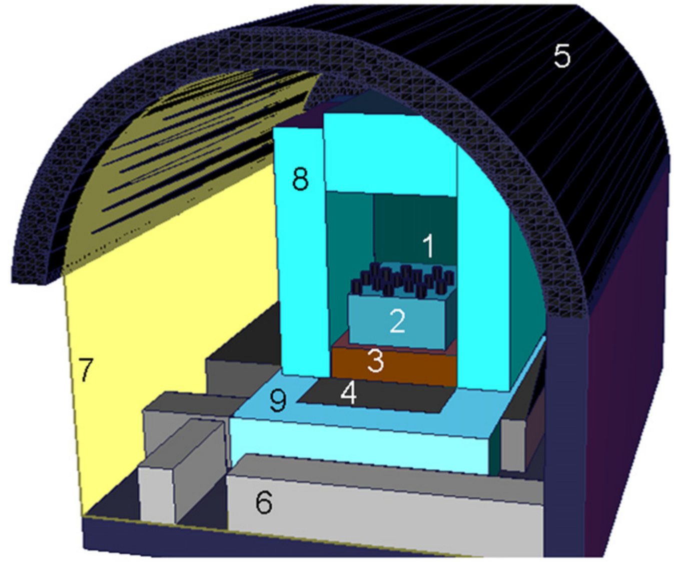

Fig. 1. Schematic view of the room and experimental set-up. 1: Detectors; 2: tank (water below the detectors); 3: wood support; 4: tank pedestal; 5: room ceiling, walls and floor; 6: concrete floor structures defining the cable conduits; 7: steel lining; 8: water shield around and above the detectors; 9: water shield around the tank pedestal.

Table 1
Measured composition of rock and concrete (in weight %).

	Concrete	Rock
SiO_2	37.20	–
Al_2O_3	3.58	–
Fe_2O_3	1.40	–
MnO	0.05	–
MgO	0.75	0.31
$CaCO_3$	55.42	99.69
Na_2O	0.67	–
K_2O	0.72	–
TiO_2	0.15	–
P_2O_5	0.06	–

Chemical analyses of rock and concrete yielded the compositions described in Table 1. Various trace metals present at the ppm level were not considered in the materials description. The analyses indicated that the amount of U in the rock is approximately half of that in concrete. Th was not identified. Values measured for other underground laboratories in continental Europe (CanFranc, Gran Sasso, Modane) [10–12] range from 2 to 70 ppb. As an estimate the average value obtained for these sites (40 ppb) is used in this work.

The composition and density of steel were assumed to be those of iron (density 7.874 g cm^{-3}). Standard compositions and densities for air (volume composition 78% N_2+21% O_2+1% Ar, density 1×10^{-3} g cm^{-3}), water (H_2O, density 1 g cm^{-3}) and glycerin ($C_3H_5(OH)_3$, density 1.261 g cm^{-3}) were used. The measured density of rock is 2.61 ± 0.01 g cm^{-3}. For concrete, a density of 3 g cm^{-3} was assumed (standard densities for ordinary Portland and heavy weight baryte concrete are 2.3 and 3.4 g cm^{-3}, respectively [13]).

In order to define the neutron source, the ^{238}U and ^{232}Th amounts for the various materials were measured or estimated (Table 2).

Samples of concrete and steel were analyzed by gamma spectrometry in order to quantify the amount of neutron emitters. From the evaluation of concrete, the detection of ^{238}Ac and ^{234m}Pa