Simulation of the SABRE South experiment and background characterization

The SABRE South Collaboration

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Abstract

SABRE (Sodium iodide with Active Background REjection) is a direct detection dark matter experiment based on an array of radio-pure NaI(Tl) crystals surrounded by a liquid scintillator veto. The achievement of an ultra-low background rate is essential to confirm or refute the DAMA/LIBRA results. The SABRE Proof-of-Principle phase has been carried out at the Gran Sasso National Laboratory, in Italy. The next phase is the SABRE-South full scale experiment at the Stawell Underground Physics Laboratory (SUPL), in Australia. A detailed simulation of the SABRE South detector has been performed in order to characterize the background for dark matter and DAMA/LIBRA modulation searches. We estimate an overall background of 0.66 cpd/kg/keV\textsubscript{ee} in the energy range 1–6 keV\textsubscript{ee} primarily due to radioactive contamination in the crystals. Based on these simulations, we expect to exclude (confirm) DAMA/LIBRA modulation at 3 (5)σ within 2 years of data taking.

1 Introduction

Within the field of Particle Physics, a leading role is played by the study of Dark Matter (DM) which represents one of the most important open problems in modern physics [1–3].

One of the fundamental search techniques for DM is direct detection. The primary goal of this method is to analyse the recoil energy released by the interaction between a dark matter particle, for a Weakly Interacting Massive Particle (WIMP) hypothesis, and detector target nuclei [4, 5]. This interaction rate should modulate annually due to the rotation of the Earth around the Sun as it moves through the galactic halo. The event rate of nuclear recoils would then be expected to follow a sinusoidal trend, having minimums and maximums due to the opposite Earth velocity directions during its orbital motion [6].

Among the several experiments operating underground, the DAMA/LIBRA experiment [7] located at the Gran Sasso National Laboratory (LNGS), in Italy, has claimed to observe an annual modulation compatible with dark matter in an array of ∼250 kg of NaI(Tl) crystals for almost two decades with a statistical significance of 12.9σ [8, 9]. Despite its longevity and high significance, the DAMA/LIBRA result is in tension with other direct detection experiments in the standard WIMP scenarios such as spin-independent dark matter-nucleon elastic scattering in the standard galactic halo hypothesis [10–13]. The most sensitive experiments use a different target material to DAMA/LIBRA, and so require the assumption of some DM interaction model to compare the result.

A model-independent test of the DAMA/LIBRA modulation is therefore best achieved with an experiment which uses the same target material and detection technique. The existing experiments are currently within 3σ of DAMA/LIBRA because of their significant level of background [14, 15].
For this purpose, the Sodium iodide with Active Back-
ground REjection (SABRE) experiment [16], is designed 
to measure the dark matter annual modulation interaction 
rate with the achievement of an ultra-low background. Di-
rect dark matter detectors are suitably well-shielded against 
external radiation and their background rate is driven by ra-
dioactive contaminants in the detector material and in the 
materials used for the construction of the experimental setup. 
Such radioactive contamination may come from long-lived, 
naturally occurring isotopes or from cosmogenic activation. 
Careful selection or development of radio-pure materials and 
equipment is therefore mandatory, as well as a detailed know-
ledge of the residual radioactivity. SABRE’s NaI(Tl) crys-
tals, photosensors and all detector materials are designed 
to reach ultra-high radio-purity levels. In addition, a liquid 
scintillator veto system allows for an active rejection of the residual 
background.

The SABRE Proof-of-Principle (SABRE PoP) phase has 
been carried out at LNGS [17] with a single 3.4 kg NaI(Tl) 
crystal. The next phase to go online will be the SABRE 
South detector at the Stawell Underground Physics Labo-
ratory (SUPL), in Australia. The detector is expected to host 
up to 50 kg of NaI crystals.

This paper provides a brief description of the SABRE 
South detector and presents a model of the expected back-
ground based on simulation and measurements of material 
radio-purity. We determine the energy spectrum expected in 
the SABRE NaI(Tl) crystals due to radioactive background 
processes. We focus in particular on the 1–6 keVee energy 
range which is the region of interest (ROI) to study the mod-
ulation and provide a prediction of the discovery and exclu-
sion power of the experiment to such signal. We also provide 
the expected total time-dependent background rate along the 
life of the experiment.

2 Detector design and implementation into simulation

2.1 Technical design

SABRE South is made up of three different subdetector sys-
tems: the NaI(Tl) crystal detector system, the liquid scintil-
lator veto system, and the muon paddle detectors. Together, 
the veto and muon systems are called the ‘outer detector’. 
These are then surrounded by steel and polyethylene shielding. 
The full experimental setup is shown in Fig. 1 (a).

The experiment can host seven NaI(Tl) cylindrical crys-
tals 25 cm long and 5 cm in radius for a mass of 7.2 kg 
per crystal (50.4 kg in total). Crystals will be grown from 
Merck’s Astrograde powder, the highest purity NaI pow-
der available, which has a potassium contamination below 
10 ppb, and uranium and thorium contamination below 1 ppt. 
These crystals are encapsulated in cylindrical oxygen-free 
high-thermal-conductivity (OFHC) copper enclosures flush-
ed with nitrogen. These enclosure modules, shown in Fig. 1 
(c), are made out of a copper cylinder with a radius of 71.5 
mm, a length of 664.5 mm and are 3 mm thick. The endcaps 
are also made out of copper and each extend the total length 
of the cylinder by 2 mm. Each enclosure contains a number 
of different components. At the centre is a NaI(Tl) cylin-
drical crystal with a length of 25 cm and a radius of 5 cm, 
shown in Fig. 1 (c) in cyan. This is wrapped in 0.2 mm of a 
PTFE foil, bookended by PTFE crystal holders, and coupled 
to a Hamamatsu R11065 PMT on each side (shown in dark 
green and blue respectively). These components are all held 
together by 9 internal support rods made of copper. Three 
are 82.5 mm long and connect the top endcap to the inner 
PTFE ring. Three more rods run from this ring through the 
two PTFE crystal holders along the length of the crystal to 
the bottom endcap and are 553.5 mm long. Finally, three 
connect the two PMT holders, which also pass through the 
crystal holders and have a length of 399 mm. The enclosures 
are submerged in the veto vessel and held in place by copper 
conduits that also allow for cabling transport out of the 
vessel.

The SABRE South veto vessel is made of stainless steel 
(lined with Lumirror) approximately 3 m tall with a 2.6 m 
diameter at its widest, and is designed to hold 10 tonnes of 
liquid scintillator. The scintillator itself is a mixture of 
Linear Alkyl Benzene (LAB) and the fluorophores PPO and 
Bis-MSB. The vessel itself is instrumented with eighteen 8” 
Hamamatsu R5912 PMTs to detect signals in the liquid scin-
tillator.

The main body of the vessel is a cylinder of height 1.65 
m and radius of 1.3 m and it is connected to spherical section 
endcaps. The interior of the vessel can be accessed from the 
top through a 70 cm diameter flange. Seven subflanges with 
a radius of 74.1 mm are mounted on top of the 70 cm diam-
eter flange, to be used for used for crystal insertion. There is 
one subflange in the center and six surrounding it disposed 
at the vertices of a hexagon. The distance between the axes 
of any adjacent pair of subflanges and thus NaI(Tl) crystals 
is 26 cm. Twelve more small flanges with a radius of 50.75 
mm are mounted on the top spherical endcap and are used 
for services, such as veto PMT cables and fluid handling. A 
triplet of aluminium pipes are placed equidistant from the 
crystal detector units and allows the insertion of radioactive 
sources for calibration purposes.

The vessel is filled to a height of 2.42 m with LAB 
and topped off with a nitrogen blanket. The eighteen vessel 
PMTs are arranged in a hexagonal pattern so that each PMT 
looks between the enclosures rather than directly at one of 
the crystals. This detector system is able to observe around 
0.12 photoelectrons/keVee, giving a detection threshold of 
around 50 keVee, and reaching 100% efficiency at 200 keVee 
and above.
The vessel is then placed within a shielding system which has a total thickness of 26 cm on the top, bottom, and sides. This is made up of a 10 cm thick layer of high-density polyethylene (HDPE) to shield from neutrons, which is sandwiched between two 8 cm layers of low-carbon aluminium killed steel to shield from high-energy gamma rays. This structure has a cuboid shape and is around 3.5 m tall and 2.9 m wide for a total mass of almost 100 tonnes. The eight EJ200 muon detector paddles sit atop this shielding forming one continuous layer covering an area of 9.6 m² and is centred above the crystals. Each paddle is instrumented with two Hamamatsu R13089 PMTs. These have a timing resolution of 200 ps, allowing for position reconstruction along the length of the paddle to within 5 cm. The threshold of this detector is on the MeV scale.

This full setup will be located at the Stawell Underground Physics Laboratory (SUPL), 1025 m underground in Victoria, Australia, providing a 2900 m water-equivalent flat overburden.

2.2 G\textsc{EANT}4 implementation

We propagate radiation through the detector with the G\textsc{EANT}4 simulation toolkit [18, 19]. The physical characteristics of the experiment are reproduced with great detail in the simulation as shown in Fig. 1 (b). The experimental components with the characteristics described in Sec. 2.1 are replicated in the simulation with the exception of muon detector, as it is made of low-radioactivity plastic and any residual radioactivity is attenuated by the shielding and so contributes negligibly to the total background model. For this reason, the simulation is more detailed closer to the crystal because the majority of the background rate comes from the crystal array itself.

Introducing extra material in the simulation would affect the background estimate as it would increase the emitted radiation, but at the same time absorb more radiation from itself and surrounding components. Therefore a great effort is put into reproducing components’ thicknesses and shapes. For the most complex component of the detector enclosure, the CAD design is transformed into gdml format and imported into the simulation. The crystal PMTs are modelled as a quartz window (with a 38 mm radius), ceramic photocathode and feedthrough plate, a PTFE voltage divider, and a Kovar body. The vessel PMTs are modelled as an ellipsoid window with a radius of 9.5 cm and body made of borosilicate. Outside of the crystal enclosures, the vessel has all the main features of the real one but it misses small details such as stud bolts, cabling, nuts and fine machining. The overall size, thicknesses and mass match the real one. These components lead to a background that is at least two orders of magnitude smaller than the crystal units and therefore further precision was not considered necessary. The simulated
shielding does not include the internal steel support frame, which amounts to approximately 10% of the total shielding mass.

For the SABRE simulation, we have chosen the shielding physics list recommended for underground low-background experiments, with the addition of the GEANT4 “option 4” for the electromagnetic (EM) physics [20]. The package for EM interactions includes the Wentzel VI model at high energy, Msc95 model below 100 MeV [21], photon models from Livermore and Penelope, and Livermore ionisation model for electrons [22, 23]. The hadronic interaction model includes elastic, inelastic, capture and fission processes; precision models are used for neutrons with energy below 20 MeV. The production and transport of optical photons both in crystal and in the LS veto have not been included in the simulation results described here; however, their inclusion is being pursued currently.

The following section details the sources of radiation with the SABRE South setup.

3 Radioactive contamination in the detector

Radioactive decays form the vast majority of background for dark matter detection with this apparatus. The most relevant sources of radioactive contamination are primordial radionuclides (238U, 232-Th and their daughters and 40K), anthropogenic radionuclides (e.g. 137Cs), cosmogenic radionuclides (e.g. 3H) and environmental radioactive noble gases, such as 222Rn and 220Rn. Contamination in the detector materials, especially in the NaI(Tl) crystal and the surrounding components, are responsible for nearly all the background rate. Therefore, a thorough assessment of the level of radioactive contamination for every component of the experimental setup is needed. The contamination levels of the materials composing the SABRE experiment are based on screening techniques such as gamma ray spectroscopy using High-Purity Ge (HPGe) detectors, neutron activation analysis (NAA), Accelerator Mass Spectroscopy (AMS), and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS).

In the following sections we list the radioactive contamination of materials used for background calculation. In some cases where the contamination level is below the sensitivity of the measurement, we consider the latter as an upper limit and conservatively use it in the simulation. Secular equilibrium in the U and Th decay chains is assumed, unless otherwise specified.

A summary of the experimental components considered in the simulation as sources of radiation, with the corresponding materials and masses, is reported in Table 1. The muon detector gives a negligible contribution to the background rate since it is located outside the passive shielding and is neither made of particularly radioactive materials, nor has a substantially large mass. We have not simulated this background, but from an approximate calculation we expect its contribution to be on the order of $10^{-12}$ cpd/kg/keV_{ee}.

| Volume Name       | Material           | # | Mass [kg] |
|-------------------|--------------------|---|-----------|
| Crystal           | NaI(Tl)            | 7 | 50.4      |
| Crystal Wrapping  | PTFE               | 7 | $2.6 \cdot 10^{-1}$ |
| Crystal Enclosure | Outer body         | Copper | 7 | 51.6     |
|                   | Inner structure     | Copper | 7 | 37.8     |
|                   | Inner structure     | PTFE | 7 | 2.8      |
| Crystal PMTs      | Window             | Quartz | 14 | 4.2 $\cdot 10^{-1}$ |
|                   | Body               | Kovar | 14 | 1.3      |
|                   | Feedthrough Plate  | Ceramic | 14 | 2.2 $\cdot 10^{-1}$ |
| Veto              | Scintillator       | LAB | 1 | 1.0 $\cdot 10^4$ |
|                   | Vessel             | Stainless steel | 1 | 1.8 $\cdot 10^3$ |
|                   | PMTs               | Borosilicate glass | 18 | 8.9 |
| Services          | Crystal conduits   | Copper | 7 | 54.4     |
|                   | Calibration pipes  | Aluminium | 3 | 4.7      |
| Shielding         | Polyethylene layer | HDPE | 1 | 6.6 $\cdot 10^3$ |
|                   | Steel layers       | Carbon Steel | 2 | 9.0 $\cdot 10^4$ |

Table 1 Components of the SABRE South experiment that have been implemented in the GEANT4 simulations, along with their material, number of times the component is used, and their total mass.

3.1 NaI(Tl) Crystals

Contamination sources within the NaI(Tl) crystals can be split into two categories: the intrinsic radiation due to naturally occurring radioisotopes in NaI(Tl) powder, and cosmogenic contamination due to activation of the Na and I when exposed to high-energy cosmic rays. Intrinsic radiation is composed of ultra-long-lived isotopes, producing a background rate that is constant over the lifetime of the detector. Cosmogenic activation is significant on the surface, but irrelevant when the crystal is placed hundreds of meters underground, since the cosmic ray flux and thus the activation rate is million of times lower. Thus, the concentration of cosmogenic isotopes in the crystals is strongly dependent on the travel time and route from the site of crystal growth to SUPL, and the length of ‘cool-down’ time allowed in the underground laboratory prior to the start of data taking. As a general rule, the cosmogenic isotopes have much shorter half-lives compared to radiogenic isotopes, leading to a time-dependent decaying background signature in the detector. The contamination levels of each are discussed separately in this section. For simplicity, we have assumed the same background model for all seven crystals.
For intrinsic radioisotopes, we assume the values reported by recent characterisation of a SABRE crystal [17, 24] where the activity of $^{40}$K, $^{210}$Pb, and $^{129}$I were computed from spectral analysis. In addition to this, $^{210}$Pb is further constrained by alpha counting, and $^{40}$K via ICP-MS measurements on crystal off-cuts. Upper limits for $^{87}$Rb, $^{238}$U and $^{232}$Th in the crystal powder are also measured with ICP-MS [25].

| Isotope | Activity [mBq/kg] |
|---------|------------------|
| $^{40}$K | $1.4 \times 10^{-1}$ |
| $^{238}$U | $< 5.9 \times 10^{-3}$ |
| $^{232}$Th | $< 1.6 \times 10^{-3}$ |
| $^{87}$Rb | $< 3.1 \times 10^{-1}$ |
| $^{210}$Pb | $4.1 \times 10^{-1}$ |
| $^{85}$Kr | $< 1.0 \times 10^{-2}$ |
| $^{129}$I | 1.3 |

Table 2 Activity levels of radiogenic isotopes in the SABRE NaI(Tl) crystals.

Cosmogenically-induced contamination in the crystals is also critical to a dark matter detector. The exposure of NaI(Tl) to cosmic rays at sea-level leads to the production of thousands of radioisotopes per kg of crystal per hour. It is therefore necessary to minimize the time spent by the crystals on the surface. Cosmogenic activation can also occur in the NaI powder prior to crystal growth. In this paper, we assume that the activation in the NaI powder is negligible compared to the activation in the NaI(Tl) crystal, since radio impurities are mitigated by the process of powder preparation and crystal growth.

The ACTIVIA [26] simulation software was used to calculate the cosmogenic activation during manufacturing and transportation of the NaI(Tl) crystals. We expect the production of a NaI(Tl) crystal at RMD (Radiation Monitoring Devices), Massachusetts, USA to take up to two months and the transportation by sea to SUPL, Victoria, Australia to take another month. Transportation via plane has been considered but disregarded due to higher cosmogenic activation despite the shorter transit time. The activation rate along the path to SUPL is corrected to take into account altitude, geomagnetic shielding and solar activity. Attenuation of the cosmogenic flux due to crystals being grown indoors and shipped in a cargo ship is not considered, therefore this estimate is expected to be conservative.

Among the cosmogenic radioisotopes, $^3$H is especially problematic as it is long-lived ($T_{1/2} = 12.3$ yr) and has a continuous beta decay spectrum with a 18.6 keV Q-value, leading to a background in the low-energy region of interest for dark matter detection. The COSINE-100 experiment has determined a $^3$H activity in its NaI(Tl) crystals at the level of 0.1 mBq/kg [27]. Thirteen other key cosmogenic isotopes have also been selected based on a cosmic-like neutron irradiation experiment and a GEANT4 neutron activation simulation.

$^{109}$Cd, $^{113}$Sn, $^{121}$Te and $^{126}$I can also deposit electrons at the low-energy range of interest to dark matter experiments. $^{126}$I has a half-life of only 12.9 days, and so should be absent inside the NaI(Tl) just months after underground placement, while the other three radioisotopes will persist for several years. $^{121}$Te is as short-lived as $^{126}$I, however it is continuously regenerated by the decay of its long-lived parent $^{121m}$Te. An equilibrium is reached quickly as $^{121}$Te decays at the same rate as $^{121m}$Te. Similarly, equilibrium is developed between $^{109}$Cd, $^{113}$Sn, $^{127m}$Te and their corresponding radio-daughters $^{109m}$Ag, $^{113m}$In and $^{127}$Te.

We consider a six-month cooling down period, beginning when the crystals arrive underground. During this period the activities of cosmogenically-induced isotopes decrease, especially for short-lived isotopes. The expected level of activity after this cooling-down period is reported in Table 3, and has been used as input to our simulations. After several years of underground operation, the only cosmogenic isotopes that contribute to the background of SABRE South are $^3$H and $^{22}$Na.

| Isotope | Activity [mBq/kg] | Half life [days] |
|---------|------------------|-----------------|
| $^3$H   | $4.1 \times 10^{-3}$ | 4496.8          |
| $^{22}$Na| $4.3 \times 10^{-2}$ | 949.7           |
| $^{109}$Cd | $5.3 \times 10^{-3}$ | 461.4           |
| $^{109m}$Ag | $5.3 \times 10^{-3}$ | $4.6 \times 10^{-4}$ |
| $^{113}$In | $1.44 \times 10^{-2}$ | 115.1           |
| $^{121m}$In | $1.41 \times 10^{-2}$ | 0.07            |
| $^{121}$Te | $0.16$           | 164.2           |
| $^{121m}$Te | $0.16$           | 19.2            |
| $^{125m}$Te | $8.35 \times 10^{-2}$ | 119.2           |
| $^{127m}$Te | $5.96 \times 10^{-2}$ | 57.4            |
| $^{127}$Te | $0.14$           | 106.1           |
| $^{125}$I  | $0.19$          | 59.4            |
| $^{126}$I  | $1.0 \times 10^{-4}$ | 12.9            |

Table 3 Radioactivity levels of cosmogenically-activated isotopes in the SABRE NaI(Tl) crystals [26]. The activity of the short-lived daughters $^{113m}$In, $^{121}$Te, $^{127}$Te, and $^{109m}$Ag are computed assuming equilibrium with their long-lived mothers $^{113}$Sn, $^{121m}$Te, $^{127m}$Te, and $^{109}$Cd, where their branching ratios are accounted for.

3.2 Crystal PMTs and reflector foil

The radioactivity levels of the crystal PMTs are based on measurements by the XENON Collaboration [28]. They have performed extensive HPGe screening of the Hamamatsu R11410 PMTs. This PMT is identical to the R11065 model used by SABRE South except for dimensions and for the
photocathode material. The measurement shows that the highest contributions in terms of radioactivity come from the Kovar body, the quartz window and the ceramic feedthrough plates. No significant contributions were attributed to the tiny amount of photocathode material; thus we assume the same for the R11065 model.

In our simulations, we model the crystal PMTs as the assembly of the three higher-radioactivity components, namely the Kovar body, the quartz window and the ceramic feedthrough plates. The contamination values assigned to them are reported in Table 4 and have been calculated from the values in Table 3 and 4 of [28], and adjusted for the difference in size/mass of each component.

We also scale up each activity for a correction factor to account for the higher radioactivity levels of some isotopes, such as $^{40}$K and $^{60}$Co, found in the assembled R11410 PMT compared to the sum of the single parts. The summed activity values from the three components match the total measured value from Table 5 of [28] and at the same time the ratios of activity levels in the three parts are kept constant and equal to those measured in the raw materials. No contamination from $^{235}$U and $^{137}$Cs was detected in [28], thus they have not been considered in this work.

PMTs are coupled to the crystal with Dow Corning optical silicone grease. Radiation originating from the optical grease and the PMT window are expected to have the same detection efficiency as the two are only $\mu$m apart. The Dow Corning radioactivity levels (< 1 ppb $^{238}$U, < 1 ppb $^{232}$Th, 1 ppm $^{40}$K) [29] are five times lower than those of the PMT window for $^{238}$U, three times lower for $^{232}$Th and 27 times lower for $^{40}$K. Moreover, the mass of the PMT window is greater by about 60 times than the mass of optical grease that will likely be used for the coupling. As such, the contribution of the optical grease to the radioactivity background is negligible.

To evaluate the background contribution from the PTFE reflector material wrapped around the crystal, we adopt measurements by CUORE-0 [30] and XENON [31]. From CUORE-0 we take the $^{210}$Pb surface contamination of PTFE $\approx 3 \times 10^{-8}$ Bq/cm$^2$, while XENON’s bulk ICP-MS measurements are used for $^{238}$U, $^{232}$Th and $^{40}$K. The PTFE reflector contamination values are listed in Table 5.

| Isotope | Activity [mBq/kg] |
|---------|------------------|
| $^{40}$K | 3.1 |
| $^{238}$U | 0.25 |
| $^{232}$Th | 0.5 |
| $^{210}$Pb | $3 \times 10^{-5}$ |

Table 5 Radioactivity levels of PTFE reflector foil [30, 31].

### 3.3 Copper and PTFE parts

The crystal enclosures and the wiring conduits that connect them to the main body of the experimental vessel consist primarily of oxygen-free high-thermal-conductivity (OFHC) copper. Following from earlier work on the SABRE PoP [32], we use the same radionuclides and their levels of activity in this work, as the material is expected to have a similar radioactive contamination. This includes the $^{238}$U and $^{232}$Th decay chains as well as $^{40}$K for the radiogenic background, which are based on levels measured by the CUORE collaboration [30]. Cosmogenically activated isotopes are also considered which were originally obtained from a study made by the XENON experiment [33]. The various isotopes considered in the simulation for this material are shown in Table 6 along with their expected activity levels.

| Intrinsic |
|-----------|
| Isotope | Activity [mBq/kg] |
| $^{40}$K | 0.7 |
| $^{238}$U | 0.065 |
| $^{232}$Th | 0.002 |

| Cosmogenic |
|-----------|
| Isotope | Activity [mBq/kg] | Half life [days] |
| $^{60}$Co | 0.340 | 1925 |
| $^{58}$Co | 0.798 | 71 |
| $^{57}$Co | 0.519 | 272 |
| $^{56}$Co | 0.108 | 77 |
| $^{54}$Mn | 0.154 | 312 |
| $^{48}$Sc | 0.027 | 84 |
| $^{59}$Fe | 0.047 | 44 |
| $^{40}$V | 0.039 | 16 |

Table 6 Relevant isotopes and their radioactive activity levels assumed for the (OFHC) copper sections of the SABRE South experiment [30, 32, 33].

In addition to the copper parts, the crystal enclosure also includes some PTFE sections which consist of a ring to interface the upper and lower copper rods, two ring-like struc-
tures to hold the crystal in place and two more rings to help secure the PMTs. These sections are shown as the dark green sections in Fig. 1 (b). We use the upper limits measured by the XENON collaboration [31] as a conservative activity for the PTFE, shown in Table 7.

| Isotope  | Activity [mBq/kg] |
|---------|-------------------|
| $^{40}$K | $<2.25$          |
| $^{238}$U | $<0.31$         |
| $^{232}$Th | $<0.16$        |
| $^{60}$Co | $<0.11$         |
| $^{137}$Cs | $<0.13$        |

Table 7 Relevant isotopes and their radioactive activity levels assumed for the PTFE sections of the SABRE South crystal enclosures. [31, 32]

3.4 Veto components: Stainless steel, PMTs and Liquid Scintillator

The veto detector contains 10 tonnes of liquid scintillator consisting of a linear-alkylbenzene (LAB) solvent, 3.5 g/L 2,5-diphenyloxazole (PPO) and 15 mg/L 1,4-bis-methylstyryl benzene (bisMSB). The purified LAB was supplied by Sinopec Jinling Petrochemical Co. Ltd, which is contracted to supply identical material for the JUNO experiment. Thus, we use the estimates of the radioactive contamination levels assumed by JUNO [34] where possible, and adopt Borexino values [35] for $^7$Be and $^{14}$C, which are not given in the JUNO work. These values are reported in Table 8.

| Isotope  | Activity [mBq/kg] |
|---------|-------------------|
| $^{40}$K | $2.71 \times 10^{-5}$ |
| $^{238}$U | $1.24 \times 10^{-5}$ |
| $^{232}$Th | $4.05 \times 10^{-6}$ |
| $^{210}$Pb | $2.08 \times 10^{-3}$ |
| $^{210}$Bi | $2.08 \times 10^{-3}$ |
| $^7$Be | $1.20 \times 10^{-6}$ |
| $^{14}$C | $4.10 \times 10^{-1}$ |
| $^{39}$Ar | $5.81 \times 10^{-6}$ |
| $^{85}$Kr | $5.81 \times 10^{-6}$ |

Table 8 Radioactivity levels assumed for the liquid scintillator. Values are taken from [34] where possible, otherwise [35].

The eighteen Hamamatsu R5912 PMTs used in the veto are primarily made from low-radioactivity borosilicate glass. The contamination of this PMT model have been measured by the DarkSide-50 collaboration [36] and are reported in Table 9.

| Isotope  | Activity [mBq/PMT] |
|---------|-------------------|
| $^{40}$K | 649               |
| $^{238}$U | 883              |
| $^{232}$Th | 110             |
| $^{235}$U | 41               |

Table 9 Radioactivity levels of the Hamamatsu R5912 Veto PMTs. Values are taken from [36].

welding to minimise the radioactivity introduced during the fabrication. Samples of the steel sheets used for the vessel construction were tested for radioactivity at LNGS using HPGe detectors. No significant levels of radiation were found, with most of the measurements at the limit of the experimental sensitivity. The averages of the measured radiation levels for each isotope are reported in Table 10.

| Isotope  | Activity [mBq/kg] |
|---------|-------------------|
| $^{238}$U | 1.5               |
| $^{232}$Th | 2.0              |
| $^{235}$U | $<1$             |
| $^{40}$K | 8                |
| $^{60}$Co | 5               |
| $^{137}$Cs | 0.5          |

Table 10 Average radioactivity levels of the stainless steel used for the SABRE veto vessel.

3.5 Passive Shielding

Samples of the Low Carbon Aluminium Killed steel forming the SABRE South passive shielding have been screened with a HPGe detector by ANSTO in Australia. A sample of the SABRE South vessel steel was also measured for comparison. No radioactive isotope was detected in either sample. The sensitivity of the measurement was approximately one order of magnitude worse than the measurement reported in Table 10. We consider conservative radioactive concentration limits in the steel based on these measurements. The radioactivity of the HDPE layers has not been measured since it is not expected to contribute significantly to the background, so limits based on radioactive measurements from XENON [31] are assumed for these background calculations.

3.6 External radiation

Preliminary measurements of environmental radiation at the designated location for the SABRE South experiment were performed prior to the construction of SUPL.

The gamma-ray energy spectrum was measured with a 3”×3” NaI(Tl) detector. The integrated flux above 100 keV
of 3 cm. The naked detector has been used to measure ther-
tubes, one of which was surrounded by a 15" diameter HDPE
were similar and we expect (α,n) transfer reactions and sponta-
tron production from (232)Th→(231)Pa→(231)Np→(232)U(n,α)
neutron spectrum from underground cosmogenic activation.

Table 11 Radioactivity levels of the shielding steel and HDPE com-
ponents.

| Isotope  | Activity [mBq/kg] | Steel | HDPE |
|----------|-------------------|-------|------|
| 238U     | <13               | 0.23  |      |
| 232Th    | <6.7              | <0.14 |      |
| 40K      | <110              | 0.7   |      |
| 60Co     | <5.5              | 0.06  |      |
| 137Cs    | <6.0              | <1.4  |      |

Table 11

amounts to 2.5 cm$^{-2}$s$^{-1}$. We expect a reduced flux after
the completion of the laboratory, since the construction materi-
als are less radioactive than the cave rock and provide pas-
itive shielding for rock-based activity.

Neutron flux was measured with two BF$_3$ proportional
tubes, one of which was surrounded by a 15" diameter HDPE
cylinder. The naked detector has been used to measure ther-
mal neutrons, while the shielded detector is sensitive to MeV
energy neutrons. We have measured a thermal neutron flux of
3·10$^{-5}$ cm$^{-2}$s$^{-1}$ and a fast neutron flux of 7·10$^{-6}$ cm$^{-2}$s$^{-1}$.
The fast neutron energy spectrum was not measured but it
was calculated using SOURCES [37]. We considered neu-
tron production from ($\alpha$,n) transfer reactions and sponta-
neous fission in the rocks. Since the spectra for the processes
were similar and we expect ($\alpha$,n) reactions from the 232Th
decay chain to be predominant, we only used the spectrum
from this reaction in the simulation. We did not consider the
neutron spectrum from underground cosmogenic activation
since this process is negligible at the depth of the experiment
(2.9 km w. e.).

4 Results

We simulated radioactive decays in different components of
the setup, according to the radioactive contamination of the
materials described in the previous sections. For every com-
bination of isotope and location inside the setup, we simu-
lated a number of events large enough to keep the sta-
tistical uncertainty in the output spectrum well below the
percent level for the crystal background and below a few
percent for the outermost volumes. While the simulation of
radioactive decays in the detector materials has been done
within a single GEANT4 simulation, the background due to
external radiation has been simulated in steps. This is nec-
essary because the probability of external radiation propa-
gating through the detector is extremely small, making it
prohibitive to produce enough statistics for a meaningful
result. We have instead separately simulated the propaga-
tion though the passive shielding and through the vessel.
We have also assumed that radiation originates uniformly
around the detector, and is directed towards the crystal array.
Since this latter assumption would significantly inflate the
background induced in the crystals, correction factors based
on the geometric acceptance of the system are applied.

The simulation records the energy deposited in the crys-
tals and the liquid scintillator. The optical simulation, mean-
ing the generation, propagation and collection of optical pho-
tons from scintillation, is not carried out in this work. In-
cclusion of optical photon propagation for each simulated
radioactive event is computationally prohibitive. However,
dedicated simulations with optical physics were used to as-
ssess energy thresholds and resolutions of the detectors. We
expected marginally better thresholds and resolutions for the
liquid scintillator system compared to the SABRE PoP and
crystal quality equivalent to that of NaI-33 [17]. We apply
an energy-dependent Gaussian smearing to the energies
recorded in the simulation, using $\sigma(E) = 1.4\% \cdot \sqrt{E}$ [MeV]
for the crystal signal and $\sigma(E) = 15.4\% \cdot \sqrt{E}$ [MeV] for the
liquid scintillator. They correspond to a resolution of 5.73% at
59.5 keV and 9.5% at 2615 keV, respectively. The en-
ergy threshold is set to 1 keV$_{ee}$ for the crystal detectors and
50 keV$_{ee}$ for the liquid scintillator.

The background contributions to the measurement of sin-
gle low-energy crystal interactions compatible with dark mat-
ter and the DAMA/LIBRA annual modulation were then
evaluated. We require a single crystal detector interaction
with energy above threshold ($>1$ keV$_{ee}$) and no energy in
the veto system above 50 keV$_{ee}$ (the “veto requirement”).
We focus on low-energy crystal interactions in the range 1–
6 keV$_{ee}$ as this is where DAMA/LIBRA observes the annual
modulation and where the WIMP signal is expected to ap-
pear. In the following, we refer to this set of requirements as
dark matter measurement (DMM) region.

4.1 SABRE South background model

The background contributions from the SABRE South com-
ponents to the crystal energy spectrum in the DMM region
are shown in Fig. 2 and the integrated rates are given in Ta-
ble 12. The table also shows the fraction of background sup-
pressed by the veto requirement.

The most significant contributions to the background come
from contamination in the crystals themselves, accounting
for more than 90% of the total 6.6·10$^{-1}$ cpd/kg/keV$_{ee}$. The
second-largest contribution comes from the components touch-
ing the crystal surfaces, with the the crystal PMTs and PTFE
wrapping producing 2.0·10$^{-2}$ and 4.5·10$^{-3}$ cpd/kg/keV$_{ee}$
respectively. Enclosure components produce a total back-
ground of 3.2·10$^{-3}$ cpd/kg/keV$_{ee}$, and the components out-
side the detector units contribute less than 10$^{-4}$ cpd/kg/keV$_{ee}$
to the total rate. These contributions are not shown in Fig. 2,
but their average rates in the DMM region are reported in Ta-
ble 12. In general, the further the component from the crys-
tal, the lower the contribution to the background. Conversely,
the veto rejection efficiency increases with distance as radiation passes through more of the liquid scintillator medium. Background from external radiation is effectively limited by the active veto and the passive shielding. External gamma background due to radiogenic processes originated in the SABRE South detector components and the actual order of magnitude of this contamination is currently unknown. The third most relevant contribution is the veto rejection efficiency increases with distance as radiation passes through more of the liquid scintillator medium. Background from external radiation is effectively limited by the active veto and the passive shielding. External gamma radiation is expected to produce order of $10^{-3}$ cpd/kg/keV$_{ee}$, which are solely due to materials within the crystal units. Other components with lower background rate are given in Table 12. The sum of all the background components is shown in solid black.

### Table 12 Background rate in the DMM region for the SABRE South components, and the corresponding veto efficiency.

| Component               | Rate [cpd/kg/keV$_{ee}$] | Veto Efficiency [%] |
|-------------------------|---------------------------|---------------------|
| Crystal intrinsic       | $5.2 \cdot 10^{-1}$      | 13                  |
| Crystal cosmogenic      | $1.2 \cdot 10^{-1}$      | 45                  |
| Crystal PMTs            | $2.0 \cdot 10^{-2}$      | 57                  |
| PTFE wrap               | $4.5 \cdot 10^{-3}$      | 11                  |
| Enclosures              | $3.2 \cdot 10^{-5}$      | 85                  |
| Conduits                | $1.9 \cdot 10^{-5}$      | 96                  |
| Liquid scintillator     | $4.9 \cdot 10^{-6}$      | $>99$               |
| Steel vessel            | $1.4 \cdot 10^{-7}$      | $>99$               |
| Veto PMTs               | $1.9 \cdot 10^{-8}$      | $>99$               |
| Shielding               | $3.9 \cdot 10^{-10}$     | $>99$               |
| External                | $0(10^{-4})$             | $>99$               |
| **Total**               | $6.6 \cdot 10^{-1}$      | 25                  |

The background from individual radioisotopes in the crystals is shown in Fig. 3, with the corresponding rate given in Table 13. Among the radiogenic contamination, the highest contributions come from $^{210}$Pb ($2.8 \cdot 10^{-1}$ cpd/kg/keV$_{ee}$) and $^{87}$Rb ($<2.2 \cdot 10^{-1}$ cpd/kg/keV$_{ee}$). The $^{87}$Rb contribution, however, is an upper limit dictated by experimental precision. No $^{87}$Rb was found with the ICP-MS measurement, and the actual order of magnitude of this contamination is currently unknown. The third most relevant contribution is $^{40}$K but this is efficiently suppressed by the veto requirement down to $1.3 \cdot 10^{-2}$ cpd/kg/keV$_{ee}$. Isotopes in the $^{238}$U chain are responsible for $5.4 \cdot 10^{-3}$ cpd/kg/keV$_{ee}$, while the $^{232}$Th chain gives $3.4 \cdot 10^{-4}$ cpd/kg/keV$_{ee}$.

The background due to cosmogenic activation in crystals is dominated by $^{3}$H, $^{113}$Sn, $^{127}$Te and $^{109}$Cd based on the crystal exposure history and cooling off detailed in Sec. 3.1.

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**Fig. 2** Crystal energy distribution in the range 0–20 keV$_{ee}$ of the background processes originated in the SABRE South detector components that pass the veto requirement. The plot shows contributions down to $10^{-3}$ cpd/kg/keV$_{ee}$, which are solely due to materials within the crystal units. Other components with lower background rate are given in Table 12. The sum of all the background components is shown in solid black.

**Fig. 3** Crystal energy distribution in the range 0–20 keV$_{ee}$ of the background due to radiogenic (top) and cosmogenic (bottom) contaminations in the NaI(Tl) crystals that pass the veto requirement. The sums of the individual components are also shown (black).
Cosmogenic backgrounds are computed limits for isotopes that were not detected and are limited by the screening measurement sensitivity. Cosmogenic backgrounds are computed after 30 days of cool-down and expected to become one order of magnitude smaller after approximately 450 days.

| Isotope | Rate, veto ON [cpd/kg/keV\text{ee}] | Rate, veto OFF [cpd/kg/keV\text{ee}] |
|---------|-------------------------------------|--------------------------------------|
| $^{210}$Pb | $2.8 \cdot 10^{-1}$ | $2.8 \cdot 10^{-1}$ |
| $^{87}$Rb | $< 2.2 \cdot 10^{-1}$ | $< 2.2 \cdot 10^{-1}$ |
| $^{40}$K | $1.3 \cdot 10^{-2}$ | $1.0 \cdot 10^{-1}$ |
| $^{238}$U | $< 5.4 \cdot 10^{-3}$ | $< 5.7 \cdot 10^{-3}$ |
| $^{85}$Kr | $< 1.9 \cdot 10^{-3}$ | $< 1.9 \cdot 10^{-3}$ |
| $^{232}$Th | $< 3.4 \cdot 10^{-4}$ | $< 3.9 \cdot 10^{-4}$ |
| $^{129}$I | $9.2 \cdot 10^{-5}$ | $9.2 \cdot 10^{-5}$ |
| Total | $< 5.2 \cdot 10^{-1}$ | $6.0 \cdot 10^{-1}$ |

Individual radioisotopes will indeed contribute differently to the background over the lifetime of the experiment due to their different half-lives. $^3$H has the longest half-life (4497 days) and will produce a nearly constant background for years. $^{113}$Sn, $^{109}$Cd have instead hundreds of days half-life and will decrease more rapidly. We expect these isotopes to contribute to the background $10^{-6}$ and $10^{-3}$ cpd/kg/keV\text{ee} respectively after five years. Some radioisotopes such as $^{127}$Te decay even faster but they can be regenerated by the decay of other isotopes ($^{127}$Xe for $^{127}$Te). We have taken into account decay and production rates of radioisotopes once the detector is underground and calculated the expected total time-dependent background rate of the experiment. Fig. 4 shows the background rate in the DMM region as a function of time from the placement of the crystals underground, i.e. once cosmic-ray exposure has ceased. The cosmogenic background is at the same level of other long lived isotopes after 30 days of cool-down and expected to become one order of magnitude smaller after approximately 450 days.

Overall, the veto requirement is expected to suppress 25% of the total background. The efficacy of the veto relies on the presence of high-energy decay products that can escape the crystals. As a number of key backgrounds (such as $^{210}$Pb and $^3$H) lack this feature, they cannot be vetoed. When penetrating radiation is emitted, as in the case of $^{40}$K, the veto efficiency increases significantly. Fig. 5 shows the background spectrum of $^{40}$K decays in the crystal with and without the veto requirement. It is worth noting that the veto is also very efficient in suppressing $^{121}$Te background, which would otherwise account for $10^{-1}$ cpd/kg/keV\text{ee} after six months of cool-down.

The presence of these energetic gamma-ray emissions also offers a method of measuring the level of contamination in the crystals. Such an analysis will be performed using coincidences between crystal detectors and/or the liquid scintillator. Fig. 6 shows the energy distributions of background events with energy deposited in one crystal and in the liquid scintillator. The excess centered around 3 keV\text{ee} of crystal energy and 1.46 MeV\text{ee} of liquid scintillator energy is due to $^{40}$K contamination in the crystal, while those at 5 and 30 keV\text{ee} crystal energy and 570 keV\text{ee} scintillator energy are due to $^{121}$Te. These excesses can also be observed in events with coincidences between two crystals and with no energy in the veto above 50 keV\text{ee} at the same energy values as shown in Fig. 7. The $^{40}$K and $^{121}$Te spread onto a

![Fig. 4 Time-dependent background rate in the DMM region.](image-url)
wider area in Fig. 6 due to the poorer resolution of the liquid scintillator compared to the crystal. Using Fig. 7 and Fig. 6, we have defined preliminary regions for the measurement of $^{40}$K and $^{121}$Te activities. The $^{40}$K measurement region A (KMA) and the $^{121}$Te measurement region A (TMA) are designed to collect events where the higher-energy gamma-ray from these decays is detected in the liquid scintillator. Events where the gamma-ray is detected in a NaI detector fall into the $^{40}$K measurement region B (KMB) and the $^{121}$Te measurement region B (TMB), instead. The selection requirements defining these regions are given in Table 14. The expected detection rate and the sample purity in each region is reported in Table 15. If the $^{40}$K and $^{121}$Te activities are similar to those assumed in this background model (see Table 2 and Table 3) a direct measurement of them in this way should be feasible with just few months of data.

4.2 Projected sensitivity of the SABRE South experiment

The sensitivity of SABRE South to a typical WIMP has also been computed. This is done assuming the spin-independent effective field theory operator $\sigma I$ from Ref. [38] and the Standard Halo Model velocity distribution. Fig. 8 shows the 90% confidence level (C.L.) limit obtained using the method detailed in Ref. [39] assuming 50 kg of target mass, three-year exposure and the constant background energy spectrum given by Fig. 2 in the 1–6 keV$_{ee}$ region. For this model we include (for comparison) the best fits to DAMA/LIBRA [9] in both the low-mass (preferential Na coupling) and high-mass (preferential I coupling) regimes, which are also reported in Table 4.2. SABRE South should be capable of excluding signal thirty-six times smaller than the DAMA/LIBRA fit for the low-mass and 8 times smaller for the high-mass regimes. The strongest limit is set at $m_\chi = 30$ GeV/c$^2$ with cross sections larger than $\sigma_\chi = 1.95 \times 10^{-42}$ cm$^2$ excluded.

We also estimate the power of SABRE South to exclude or confirm the DAMA/LIBRA annual modulation signal [9],
assuming a background constant in time. This assesses the ability of SABRE South to observe a signal with a modulation of 0.0119 cpd/kg/keV, and a constant rate of 1.36 cpd/kg/keV, (taken from the upper limits given in Ref. [40]), and is shown in Fig. 9. Based on these results, with 2 (6) annual cycles of data, SABRE South will be able to refute the interpretation of the DAMA/LIBRA modulation as a dark matter signal with 3σ (5σ) C.L.. More importantly, in the event of observation of the annual modulation, this signal would reach a significance of 5σ C.L. with two full years of data.

### 5 Conclusions

We have evaluated the expected background of the SABRE South experiment due to radioactive emissions from the detector components and the external environment. This prediction is based on a Monte Carlo simulation of the experiment combined with measurements (or assumptions) of the radiation levels within the detector materials. The simulation carefully reproduces the design of the apparatus, with particular attention to the parts close to the crystal detector.

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**Table 14** Definition of $^{40}$K and $^{121}$Te measurement regions.

| Region  | Total rate [cpd] | Sample purity |
|---------|------------------|---------------|
| KMA     | 13               | 90%           |
| KMB     | 0.32             | > 99%         |
| TMA     | 130              | 90%           |
| TMB     | 3.2              | > 99%         |

**Table 15** Expected event rate and sample purity in the $^{121}$Te and $^{40}$K measurement regions.

| $m_\chi$ [GeV/c$^2$] | DAMA/LIBRA fit | SABRE South limit |
|-----------------------|----------------|-------------------|
| 11.6 ± 0.5            | 7.3 ± 0.6 · 10^{-40} | 2 · 10^{-41}     |
| 65.9 ± 4.8            | 4.2 ± 0.7 · 10^{-41} | 5 · 10^{-42}     |

**Table 16** Best fits to the DAMA/LIBRA data [9] for the spin-independent $\theta/1$ [38] in the low- and high-mass regions and SABRE South’s exclusion limits.

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**Fig. 8** 90% exclusion curve for the SABRE South experiment after three years of data taking (in blue) assuming a background model in the 1–6 keV$_{ee}$ region given by Fig. 2 and an exposure mass of 50 kg. The best fits to the DAMA/LIBRA data for this model in both the low- and high-mass region are shown in pink.

We find that the contamination of the crystals gives the most significant contribution to the radioactive background in the DMM region (> 90% of the overall background), confirming the importance of lowering the crystal contamination as much as possible. The radio-purity of the crystals, combined with the active veto technique, allows SABRE to achieve a background of 0.66 cpd/kg/keV$_{ee}$ in the 1–6 keV$_{ee}$ energy region, where the modulation signal was observed by DAMA/LIBRA. This background rate includes a 0.22 cpd/kg/keV$_{ee}$ contribution from the upper limit estimate of $^{87}$Rb in the crystals. No $^{87}$Rb contamination has been reported by other NaI(Tl) experiments so far, thus the total background rate for the SABRE South experiment might be lower than what is reported here.

The dominant contribution within the crystals is expected to be from bulk contamination of $^{210}$Pb in the crystals (0.28 cpd/kg/keV$_{ee}$), followed by production of $^3$H in the crystals during exposure to cosmic rays (3.4 · 10^{-2} cpd/kg/keV$_{ee}$).
Fig. 9 The exclusion and discovery power of SABRE South for a DAMA/LIBRA-like signal. The shaded regions indicate 1σ statistical uncertainty bands.

Based on this simulated background, which does not include PMT noise, SABRE South is expected to reject the DAMA/LIBRA modulation at 3σ (in the case of null results) or confirm it at 5σ (in the event of observation of a compatible modulation) within 2 years.

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