The SABRE South Experiment at the Stawell Underground Physics Laboratory


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The SABRE (Sodium iodide with Active Background REjection) experiment aims to detect an annual rate modulation from dark matter interactions in ultra-high purity NaI(Tl) crystals in order to provide a model independent test of the signal observed by DAMA/LIBRA. It is made up of two separate detectors; SABRE South located at the Stawell Underground Physics Laboratory (SUPL), in regional Victoria, Australia, and SABRE North at the Laboratori Nazionali del Gran Sasso (LNGS).

SABRE South is designed to disentangle seasonal or site-related effects from the dark matter-like modulated signal by using an active veto and muon detection system. Ultra-high purity NaI(Tl) crystals are immersed in a linear alkyl benzene (LAB) based liquid scintillator veto, further surrounded by passive steel and polyethylene shielding and a plastic scintillator muon veto. Significant work has been undertaken to understand and mitigate the background processes that take into account radiation from detector materials, from both intrinsic and cosmogenic activated processes, and to understand the performance of both the crystal and veto systems.

SUPL is a newly built facility located 1024 m underground (~2900 m water equivalent) within the Stawell Gold Mine and its construction was completed in mid-2022. It will house rare event physics searches, including the SABRE dark matter experiment, as well as measurement facilities to support low background physics experiments and applications such as radiobiology and quantum computing. The SABRE South commissioning is expected to occur this year.
1. Introduction

The nature of dark matter is one of the longest unsolved puzzles in modern physics with evidence mounting for almost a century on all cosmological scales. Particle dark matter (in particular WIMPs) remains one of the most promising solutions and has motivated decades-long searches [1]. Direct detection experiments aim to observe the scatter of WIMPs off standard model particles as they pass through the Earth, observed primarily as a recoil in a target material. Only one experiment to date - DAMA (and later DAMA/LIBRA) has claimed to observe such a signal, reporting a 12.9 $\sigma$ annual modulation signal consistent with the WIMP-like dark matter hypothesis [2]. Despite this highly significant result, no other experiment has been able to confidently reject or confirm this signal in this region of parameter space using the same NaI target crystals, motivating longer and lower background direct detection experiments to resolve this tension. The SABRE experiment aims to provide a model independent test of the DAMA/LIBRA result using ultra-low background target crystals. SABRE will operate in two separate hemispheres: SABRE North, operating at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and SABRE South, at the Stawell Underground Physics Laboratory (SUPL) in Australia [3][4]. Both SABRE North and South will attempt to detect the annual-modulation signal predicted by the relative motion of the Earth’s solar orbit. The experiment will use high purity thallium-doped sodium iodide crystals as a target for the dark-matter nuclear-recoil signals. SABRE South will also submerge the target crystals in 12 kL of linear alkylbenzene (LAB) as an active veto to suppress background processes, and implement a separate muon veto to measure the cosmic-ray flux and reject extrinsic cosmogenic backgrounds. One of the key requirements for the SABRE experiment is a sufficiently low background to provide significant results in probing the DAMA hypothesis in a timely manner. To achieve this, SABRE aims for a total background less than 1 cpd/kg/keV, a value we have demonstrated based on our latest simulation results.

2. SABRE South and the Stawell Underground Physics Laboratory (SUPL)

SABRE South will operate in the newly constructed Stawell Underground Physics Laboratory (SUPL), approximately 240 km north-west of Melbourne, Australia. The laboratory was constructed in a disused section of a still-active gold-mine, and is situated 1025 m underground, accessed via a helical drive shaft. The laboratory has a flat rock-overburden, primarily consisting of basalt which provides 2870 m of water-equivalent shielding, providing a factor $10^6$ reduction in the muon flux. The laboratory has been sealed with low radioactivity shotcrete walls and Tekflex to suppress radon flow into the lab through the walls. A radon reduction system has been designed and will be implemented in the future as SABRE South comes online.

The SABRE South detector itself is designed to detect dark matter with seven NaI(Tl) target crystals with a combined mass ranging between 35 and 50 kg (see the discussion on the NaI(Tl) detector system). The experiment consists of three sub-detector systems: the NaI(Tl) crystal system, the linear alkylbenzene (LAB) liquid scintillator system, and the plastic scintillator muon detectors. The liquid scintillator and muon detectors work together as an active veto for SABRE, rejecting events from both intrinsic and extrinsic background sources.
The NaI(Tl) crystals are each coupled to two Hamamatsu R11065 PMTs and sealed in an oxygen-free high-conductivity copper enclosure, which is flushed with nitrogen. The crystal enclosures are then submerged in the 12 kL liquid scintillator system within the SABRE South vessel. Finally the muon detector layer is placed above the vessel, outside the passive shielding enclosure made of polyethylene and steel.

The experiment has 48 main PMT signal channels read out over six CAEN digitisers. Five V1730 digitisers at 500 MS/s will be used for the crystal and liquid scintillator sub-modules, and one V1743 digitiser will acquire the muon veto’s 16 channels at 3.2 GS/s. These are all processed live by custom acquisition software written in C++, compressed, and regularly saved off-site at the University of Melbourne. The raw data will then be processed by SABRE’s bespoke python-based data processing and transformation software tool Pyrate.
3. \textbf{NaI(Tl) detector system}

The SABRE South crystals are in their final R&D stage, with the background contamination and light yield well understood from previous test crystals. We are considering two options for the final mass of our crystals: a total mass of 35 kg and a total mass of 50 kg. In both cases, the expected light yield is $\geq 10$ PE/keV. The key difference in the two scenarios arises from the additional process of zone refining for the lower mass crystals. This extra processing step slowly heats the NaI linearly, transporting impurities to a single end to be discarded, thus reducing the intrinsic background but also reducing the total mass. For the 50 kg crystal, the total intrinsic background is expected to be $\leq 0.52$ cpd/kg/keV, while the zone-refined crystals have a background $\leq 0.27$ cpd/kg/keV. The final sensitivity for SABRE will ultimately depend on this design choice - determining the total mass and background for a given exposure time. Provided that the total background is indeed reduced, it is possible to achieve timely results with the reduced mass crystals. The trade-off for the two scenarios is summarised in the following two figures [5]. To achieve $5\sigma$ discovery with $< 3$ years of data taking, the 50 kg scenario requires a total background of $< 0.7$ cpd/kg/keV, and the 35 kg scenario $< 0.5$ cpd/kg/keV.

![Figure 3](image)

Figure 3: The time in years required for SABRE to reach $3\sigma$ exclusion (left) and $5\sigma$ discovery (right) for the DAMA modulation signal as a function of exposure mass and total background. The light and dark blue lines overlaid demonstrate approximate trends for experimental exposure times of interest.

4. \textbf{Simulation and liquid scintillator active veto}

A simulated version of the SABRE South vessel was created using \texttt{Geant4} to model the anticipated background radiation [4][5]. The main source of background, comprising over 90% of the contributions, is predicted to be radioactive contamination in the NaI(Tl) crystals, primarily from $^{210}$Pb (0.28 cpd/kg/keV$_{ee}$). The next significant background source is cosmogenic activation of the crystals during their transportation from the production facility to SUPL, adding an additional 0.16 cpd/kg/keV$_{ee}$. Predominantly from $^3$H, the cosmogenic background is time-dependent (decreasing over the life of the experiment) and as such the initial yield needs to be well understood.
Figure 4: Left: radioactive background as a function of energy deposited in the SARBE South crystals in the 0-20 keV range, with the total sum shown in black. Right: $^{40}$K decay rate in the crystal in the 0-20 keV range, with effect of the veto on and off.

$^{40}$K is the next most relevant background for SABRE, reaching its peak in the 1-6 keV$_{ee}$ region of interest. Reducing this background is the main purpose of the liquid scintillator veto system, but it is important to note that the liquid scintillator also works extremely well as a shielding system and removes almost all background contributions external to the crystals. An energy threshold of 50 keV is chosen for efficiency calculation purposes. The LS detector is capable of vetoing $^{40}$K with about an 87% efficiency. Overall the veto efficiency for the crystal intrinsic radioenics is 13.3%. The relatively low total veto efficiency is because some of the contaminants produce decays that are not able to be vetoed: e.g. $^{87}$Rb, decaying via a single $\beta$ particle and thus not depositing any energy in the liquid scintillator. Overall, it is expected that SABRE South will have a background below 0.72 cpd/kg/keV, approximately four times lower than the values reported by both COSINE and ANAIS [7] [8].

<table>
<thead>
<tr>
<th>Radiogenic Isotope</th>
<th>Rate, veto ON [cpd/kg/keV]</th>
<th>Rate, veto OFF [cpd/kg/keV]</th>
<th>Veto efficiency [%]</th>
</tr>
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<tbody>
<tr>
<td>$^{210}$Pb</td>
<td>$2.8 \cdot 10^{-1}$</td>
<td>$2.8 \cdot 10^{-1}$</td>
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</tr>
<tr>
<td>$^{87}$Rb</td>
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<td>$&lt; 2.2 \cdot 10^{-1}$</td>
<td>0.0</td>
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<td>$^{40}$K</td>
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<td>$1.0 \cdot 10^{-1}$</td>
<td>87.0</td>
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<tr>
<td>$^{238}$U</td>
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<td>$&lt; 5.7 \cdot 10^{-3}$</td>
<td>5.3</td>
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<tr>
<td>$^{85}$Kr</td>
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<td>$&lt; 1.9 \cdot 10^{-3}$</td>
<td>0.0</td>
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<tr>
<td>$^{232}$Th</td>
<td>$&lt; 3.4 \cdot 10^{-4}$</td>
<td>$&lt; 3.9 \cdot 10^{-4}$</td>
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<tr>
<td>$^{129}$I</td>
<td>$9.2 \cdot 10^{-5}$</td>
<td>$9.2 \cdot 10^{-5}$</td>
<td>0.0</td>
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<tr>
<td><strong>Total</strong></td>
<td>$&lt; 5.2 \cdot 10^{-1}$</td>
<td>$&lt; 6.0 \cdot 10^{-1}$</td>
<td>13.3</td>
</tr>
</tbody>
</table>

Table 1: Background rate in the DM region of interest from intrinsic crystal contamination. Each contribution is listed with both the veto off and veto on.
5. Muon detector system

SABRE South will operate a muon veto above the shielding as shown in Figure 2 to tag and veto muon events from dark matter searches. While the muon rate in SUPL will be relatively low, muon fluxes are known to modulate annually, therefore the flux in SUPL must be measured over the lifetime of SABRE. This system (in conjunction with the main veto vessel) will also be used to characterise and measure the muon flux, measuring the annual modulation and angular distribution. The detector system is comprised of eight EJ-200 plastic scintillator modules measuring $3000 \times 400 \times 50$ mm with trapezoidal PMMA light guides at each end, funneling the scintillation light into two Hamamatsu R13089 PMTs (230 ps transit time spread). The muon PMT signals are digitised in a CAEN V1743 digitiser at 3.2 GS/s. Prior to installation above SABRE (in the coming months), these modules will begin their preliminary characterisation of the muon flux in SUPL - the first active detection system in the new laboratory. The muon flux in SUPL has been estimated using CRY for the initial surface flux and Geant4 for muon propagation down to and through the detectors in SUPL in [5].

Figure 5: Angular (left) and energy (right) distribution of underground muons based on the Gaisser formulation. The red curves are the expected distributions for SUPL, and the red points correspond to the simulated results from CRY and Geant4. The areas under the curves are normalised to 1.

Figure 6: Left: time difference for muons passing through and isolated positional along a single muon detector panel. Right: relationship between the time difference for scintillation events, and their known position.

The dual PMT readout of each of the muon detector panels allows for the position of incident...
particles to be determined. Using two 2.5 cm wide scintillator trigger modules placed at regular positions along the length of a single muon veto panel, the position-time difference dependence of the detector was measured. At each position we captured the full-coincident signals of incoming cosmic muons. By scanning the external trigger module along the detector, we have demonstrated this system is capable of a timing resolution of ~400 ps, and thus the muon detectors are capable of providing a ~5 cm position resolution along the longest dimension of the detector. Combining the tracking information from the muon detector and the LS veto vessel below, SABRE South will be able to perform particle identification of the incoming cosmic rays. A scaled combined muon detector and liquid scintillator setup has been previously used to demonstrate the efficacy of using time-of-flight between the two sub-detectors for tagging, and the discrimination of incident muons from neutrons [5].

6. Conclusion

With the newly constructed Stawell Underground Physics Laboratory now operational, the efforts to commission the SABRE South experiment are well underway. Calibration of the sub-detector systems has nearly been completed, and first measurements from SUPL are expected to be taken in the coming months. SABRE’s NaI(Tl) crystal production is expected to commence in the final quarter of 2023. SABRE is well placed to provide insight into the DAMA/LIBRA results in a timely manner - assuming the Standard Halo Model, SABRE South is projected to either reject the DAMA/LIBRA modulation at a significance level of 3σ or confirm it at 5σ within 2.5 years of collecting live data.

References

[1] Particle Data Group collaboration, Review of Particle Physics, PTEP 2022 (2022) 083C01.


