PROCEEDINGS OF SCIENCE

The SABRE South Experiment at The Stawell Underground Physics Laboratory

Kieran J. Rule on behalf of The SABRE South Collaboration[a,b]

[a] *School of Physics, The University of Melbourne, Victoria 3010, Australia*

[b] *ARC Centre of Excellence for Dark Matter Particle Physics, Australia*

E-mail: kjrule@student.unimelb.edu.au

SABRE is a dark matter direct detection experiment designed to confirm or reject the proposed dark matter measurement of the DAMA/LIBRA experiment. SABRE is a dual hemisphere experiment with detector units in the Northern (SABRE North) and Southern Hemisphere (SABRE South). The Southern Hemisphere location of the SABRE South Experiment provides unique background discrimination capability since annual modulations originating from seasonal effects will have an opposite phase to a dark matter annual modulation. SABRE South is located at the Stawell Underground Physics Laboratory (SUPL), in regional Victoria, Australia. SUPL is the first deep underground physics laboratory in the Southern Hemisphere, with a 2900 metre water-equivalent overburden. This proceeding provides an overview of the SABRE South Experiment and an update on its overall progress in SUPL.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

PoS(EPS-HEP2025)119

1. Introduction

For over a century the existence dark matter has posed one of the largest open questions in physics. If particle dark matter is dispersed throughout the galactic halo of the Milky Way, then the interaction rate of dark matter with terrestrial detectors will have some modulating component caused by the motion of the Earth around the sun as the sun moves through the galactic dark matter halo, and a non-modulating component due to the constant motion of the sun in the galactic reference frame. The modulating component is of order 1% of the constant component, since the rotation of the Earth around the sun accounts for a small fraction of its total velocity in the rest frame of the Milky Way.

The only reported measurement of such a signal is the annually modulating excess in scintillation events seen by the NaI(Tl) detectors DAMA/LIBRA and DAMA/NaI [1]. In NaI(Tl) detectors, an ionising particle passing through NaI(Tl) crystals cause energy transitions of the atoms and electrons. The crystal emits photons upon de-excitation that are measured using photomultiplier tubes (PMTs). This phenomenon could be used to measure the differential interaction rate of dark matter with the crystal. The scintillation response of NaI(Tl) detectors means they are highly suited of probing the dark matter parameter space associated with the class of theorised dark matter particle the Weakly Interacting Massive Particle (WIMP). WIMPs interact with Standard Model particles with weak scale cross-sections, and are largely motivated by the observed relic density of dark matter matching the relic density of a weak-scale particle (100-1000 GeV/c^2) produced by freeze out [2, 3]. The parameter space associated with the recoil energy of a spin independent WIMP with Na or I nuclei, have been ruled out by several noble liquid scintillators [4–6]. To date, no satisfactory explanation of the result from DAMA/LIBRA has been found. Efforts to unambiguously confirm or refute the signal from DAMA/LIBRA are ongoing in several experiments, including The SABRE South Experiment, using the same target material, allowing for a dark matter model independent analysis of signal from DAMA/LIBRA.

2. The SABRE South Detector

SABRE is a dark matter direct detection experiment that aims to confirm or reject the proposed dark matter measurement of the DAMA/LIBRA experiment [7, 8]. SABRE is designed as a dual hemisphere detector with detector units in the Northern and Southern Hemisphere. This will allow for greater background discrimination since annual modulations originating from seasonal effects will have opposite phases in the Northern and Southern Hemispheres, whilst annual modulations originating from the galactic dark matter halo will have the same phase at each detector [9]. Due to this effect, SABRE South will be equipped to uniquely understand what is the cause of the DAMA/LIBRA modulation [10].

SABRE South is the Southern Hemisphere component of SABRE. It is located 1024 m underground at the Stawell Underground Physics Laboratory (SUPL) in the Stawell Gold Mine. SUPL has a flat 2.9 km water equivalent overburden that reduces the cosmogenic muon flux background by a factor of 10^6 [7].

SABRE South consists of a 50 kg NaI(Tl) target with active background rejection. A schematic of the SABRE South detector is shown in Figure 1. The apparatus consists of three sub-detector

PoS(EPS-HEP2025)119

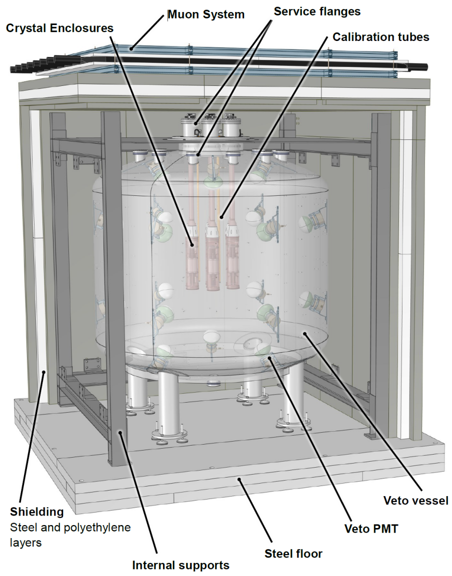

Figure 1: Detailed 3D render of the SABRE South experimental set up.

systems: the NaI(Tl) crystal detector, the linear alkyl benzene liquid scintillator system, and the muon detectors. Together the liquid scintillator and muon detectors act as an active veto system.

The detector is enveloped in 125 tons of steel to shield the apparatus from ambient radioactivity. The NaI(Tl) crystal detector consists of an array of seven NaI(Tl) crystals, each coupled to two photo-multipliers, seated in 11.6 kL of liquid scintillator contained in a steel vessel. The vessel is surrounded by steel and polyethylene shielding and sits underneath eight muon detectors covering a 9.6 m^2 area. The muon system will provide important information regarding the seasonal muon variation for SABRE South. The array of 32 veto PMTs submerged in the liquid scintillator comprises the active veto system which will give SABRE South better discrimination between background events caused by radioactive decay or neutrons, and non-background signal events. Radioactive decays proceeding by alpha or beta emission, particularly in the crystal, require vetoing to avoid miss-attribution as dark matter signal events. For SABRE South, coincident gamma rays are detected by the veto PMTs surrounding the crystal array. The veto is projected to give an order of magnitude reduction in background events [9].

The active background rejection of SABRE South, as well as its high radiopurity crystals, will allow it to have a background of 0.72 cpd/kg/keV in the 1-6 keV region. As a result SABRE South will be able to reject or confirm the DAMA/LIBRA modulation to 5σ, within 3.5 or 2 years respectively. This background was calculated in reference [11] by combining simulation and measurements of decays from radio-impurities in the crystal and surrounding detector components, combined with reduction from the active veto system. The experiment has been designed such that the background external to the crystal is 10% of the total.

PoS(EPS-HEP2025)119

3. NaI(Tl) Crystals

SABRE South requires an extremely low crystal background to achieve a statistically significant test of DAMA/LIBRA. SABRE South plans on operating with 7×7 kg crystals produced using the Bridgman method. SABRE South's total crystal background was modelled in reference [11], and

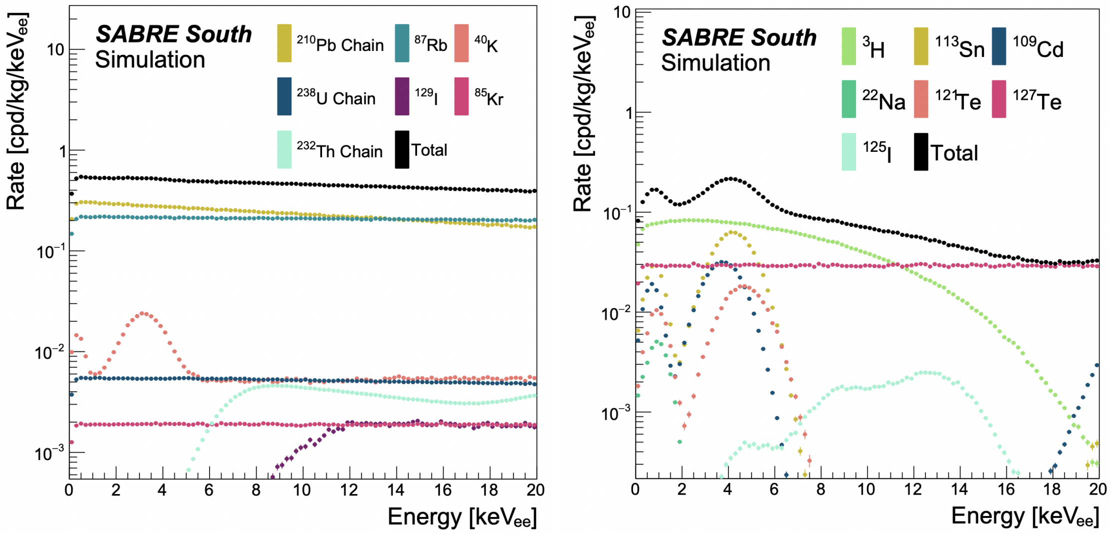

Figure 2: Crystal energy distribution in the range 0–20 keVee of the background due to radiogenic **(left)** and cosmogenic **(right)** contaminations in the NaI(Tl) crystals after a 6 month cool-down period. The sums of the individual components are also shown (black) [11].

can be seen in Figure 2. The most important crystal intrinsic backgrounds for SABRE South in the 1-6 keV region of interest are the ^{3}H, ^{40}K, ^{210}Pb. The ^{3}H is introduced via cosmogenic activation during transportation of the crystal and decays through the emission of an electron resulting in 5 keV$_{ee}$energy depositions in the crystal. ^{3}H has a half life of 12 years meaning it will be a time dependent background throughout the life of any NaI experiment. ^{40}K is introduced as an impurity in the powder prior to crystal production. It produces a 3.2 keV$_{ee}$ electron via beta decay. The ^{210}Pb is introduced during the crystal growth process due to contamination in water and in the powder, as well as the plate-out of airborne Rn. SABRE South has procured Astro Grade powder with an extremely low Rn and K contamination [12, 13]. The procurement of low contamination powder and development of new NaI(Tl) growth techniques has allowed SABRE South to produce lower background crystals than those of COSINE-100 [14] and ANAIS-112 [15], and the active veto system decreases this background below the level of DAMA/LIBRA [1]. Table 1 shows purity levels from some of the most active crystal contaminants across NaI(Tl) detector experiments.

The systems associated with the NaI(Tl) detector modules are highly complex, driven by the need to protect the NaI(Tl) from moisture, radon and other environmental effects during handling, assembly, and insertion of the NaI(Tl) detector modules. Each NaI(Tl) detector module has two 76 mm diameter Hamamatsu R11065 PMTs coupled to it. These PMTs were chosen for their high sensitivity to single photons, low noise rates, and low radioactive background. Notably, only PMTs with quantum efficiency > 30% were procured, in order to achieve a high single-photon detection efficiency.

Experiment	^{39}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Pb (mBq/kg)
DAMA/LIBRA [16]	13	0.7–10	0.5–7.5	$(5–30) \times 10^{-3}$
ANAIS-112 [17]	31	< 0.81	0.36	1.53
COSINE-100 [18]	35.1	< 0.12	< 2.4	1.74
SABRE (NaI-33) [12]	4.3	0.4	0.2	0.34

Table 1: Purity levels of NaI(Tl) crystals of various experiments.

4. Cosmogenic Muon Flux Measurement

As outlined above, cosmogenic muons are one of the most important time dependent backgrounds for annual modulation experiments to understand, due to their seasonal variation. Reducing the cosmogenic muon flux motivates the deep underground position of SABRE South. A reliable measurement of the underground cosmic muon flux provides a crucial baseline for future experiments hosted at SUPL, including SABRE South. This measurement employed the SABRE South muon veto system, comprises eight EJ200 plastic scintillator panels (5 cm thick, 3.0 m × 0.4 m each) read out by Hamamatsu R13089 photomultiplier tubes at both ends. For this measurement, the panels were arranged in a telescope configuration with two orthogonal orientations, enabling angular selection of through-going muons. Waveforms from 16 channels were digitised with a CAEN V1743 unit at 3.2 GS/s. Data were acquired over 236 live days between April 2024 and early 2025. The campaign was divided into three phases to optimise PMT voltages and trigger conditions. Environmental conditions (temperature, pressure, and vibration) were monitored with a slow-control system to ensure stability of the measurement.

Muon candidates were selected using coincident triggers across top–bottom panel pairs. Detector performance was quantified using above-ground tests to measure the single-panel efficiency,

$$\varepsilon = (99.42 \pm 0.03_{\text{stat}} \pm 0.23_{\text{sys}})\ \%.$$

The geometric acceptance of the telescope was evaluated with Monte Carlo simulations. Detailed material densities of the local overburden (basalt and sandstone) were incorporated, provided by Stawell Gold Mine, allowing for a highly precise acceptance calculation. The simulated acceptance map is used to filter the flux distribution, calculated using the overburden data. Each flux bin is multiplied by the corresponding acceptance. The result is shown on the right in Figure 3.

After applying efficiency and acceptance corrections, the preliminary flux was determined to be

$$f = (5.586 \pm 0.031_{\text{stat}} \pm 0.290_{\text{sys}}) \times 10^{-8}\ \text{cm}^{-2}\,\text{s}^{-1}.$$

This value is in line with expectations for a flat overburden of ~2.8 km water-equivalent and is comparable to that observed at Boulby and Kamioka, as shown in Figure 3. Cosmogenic muon flux seasonal modulation measurements are ongoing. A full analysis of the measurement is in preparation for submission to Astroparticle Physics.

PoS(EPS-HEP2025)119

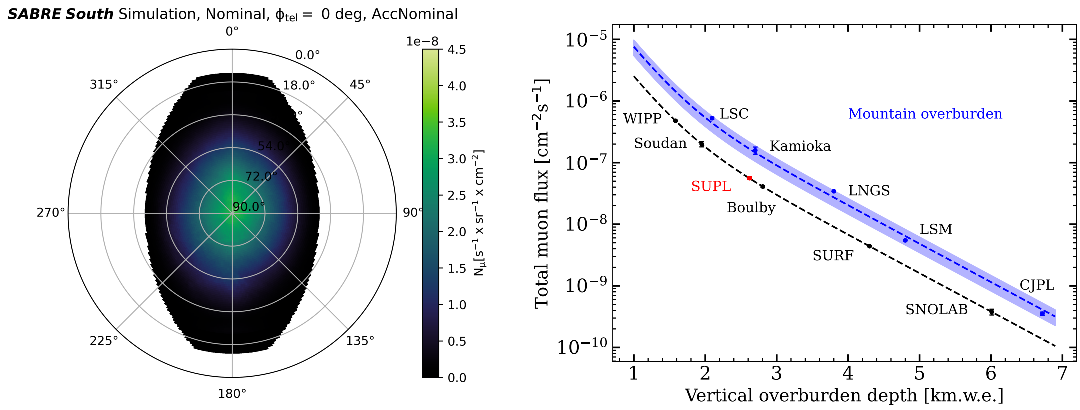

Figure 3: Left: Simulated muon flux at SUPL as a function of the elevation and azimuth using PUMAS [19, 20]. The detector acceptance has been taken into account, considering the nominal orientation of the detector with its length ranging from North to South. In these plots, the vertical inclination of the muon is parameterised by the elevation defined as $\eta = 90° - \theta$. Right: The total muon flux at several underground physics laboratories as a function of vertical overburden depth.

5. The DAMA/LIBRA signal: an induced modulation effect?

The efficacy of the background subtraction method used by DAMA/LIBRA has been a matter of debate due to work by the COSINE-100 Collaboration [21], and Buttazzo et al. [22]. The background subtraction method can be desribed by

$$R_i = \langle r_{ijk} - flat_{jk} \rangle_{jk}, \tag{1}$$

where R_i is the residual at the ith time interval, r_{ijk} is the detection rate in the jth photomultiplier detector in the kth energy bin over the ith time interval, and $flat_{jk}$ is the average rate of the jth detector in the kth energy bin for one data taking cycle (approximately yearly). This is averaged over all detectors and energy bins in the considered energy region. Since the data collection periods of DAMA/LIBRA are approximately annual cycles, with an average beginning in August, this background subtraction method may induce a yearly periodicity to the residual distribution. However, a yearly modulation will only be induced in the residuals distribution if there is a time-dependent background present. To study this effect we apply the background subtraction method used by DAMA/LIBRA to a best-faith replication of their background, and consequently show that bias induced from this background subtraction could not be the cause of the signal seen by DAMA/LIBRA.

In the absence of a detailed background model from DAMA/LIBRA, we use the SABRE South NaI(Tl) crystal background model [11] and scale the two largest time-dependent contributions, ^{3}H and ^{210}Pb to match the upper limit reported by DAMA/LIBRA. We apply Equation 1 and perform fits to the residuals of Monte Carlo realisations of this background model. Figure 4 shows results from 1000 fits to simulated backgrounds using the background model described above, designed to replicate DAMA/LIBRA's background. We used two different assumptions on the initial activity of ^{3}H. Shown in yellow is the upper-limit reported by DAMA/LIBRA, and in blue is a revised ^{3}H activity that we calculated based on the activation of ^{3}H in NaI crystals with 125 days of surface

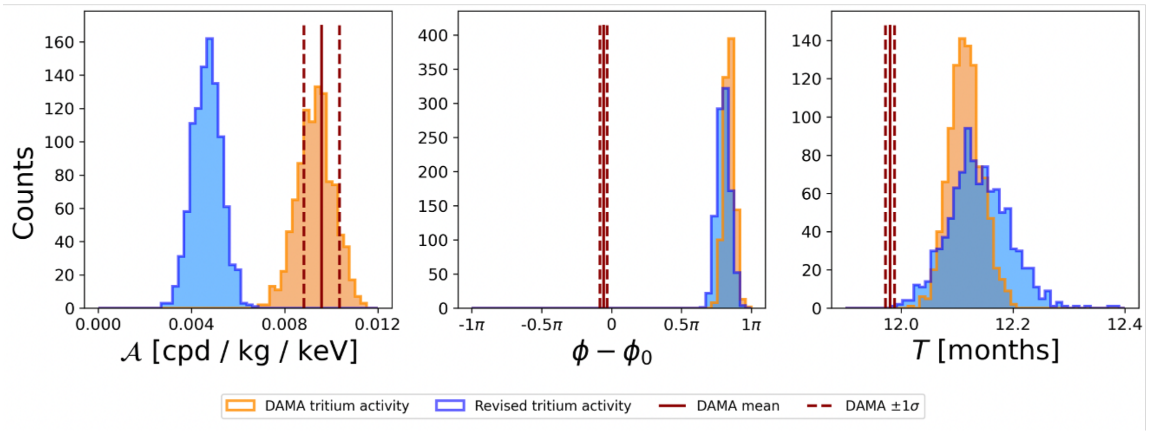

Figure 4: Results of 1000 toy residuals fits to MC realisations of the background model described in text, aim to replicate DAMA/LIBRA's background. We show the distributions of amplitude, phase and period of the oscillating fit function for two different assumptions on the initial activity of 3H. These are the 'DAMA tritium activity' corresponding to the DAMA-reported upper limit of 0.09 mBq/kg, and the 'revised tritium activity' corresponding to the 0.031 mBq/kg initial activity estimate discussed in the text. For comparison we show the results reported by DAMA in each case [8].

exposure. We can see that the modulation caused by this background subtraction method cannot reproduce the phase or period of the signal measured by DAMA/LIBRA, thus cannot be the cause of their signal.

6. Conclusion

The SABRE South Experiment at The Stawell Underground Physics Laboratory is the first dark matter direct detection experiment in the Southern Hemisphere, and is designed to provide a dark matter model independent test of the longstanding annual modulation signal measured by DAMA/LIBRA. It's active background rejection and Southern hemisphere location provide it a unique ability to discriminate seasonal backgrounds. The SABRE South Experiment will utilise 50 kg of ultra-high purity NaI(Tl) crystals to reach the lowest background of any NaI(Tl) detector of 0.72 cpd/kg/keV in the 1-6 keV region. The muon veto system has been successfully setup in The Stawell Underground Physics Laboratory with the first flux measurement to be published soon. The experiment is currently in commissioning with full operation expected in 2026. The SABRE South Experiment will be able to reject or confirm the DAMA/LIBRA modulation to 5σ, within 3.5 or 2 years data taking, respectively.

References

[1] DAMA/LIBRA collaboration, *The DAMA project: Achievements, implications and perspectives*, *Progress in Particle and Nuclear Physics* **114** (2020) .

[2] F. Queiroz and S. Farinaldo, *WIMP theory review*, *PoS* **EPS-HEP2017** (2017) [1711.02463].

[3] M. Schumann, *Direct Detection of WIMP Dark Matter: Concepts and Status*, *J. Phys. G* **46** (2019) 103003 [1903.03026].

[4] LUX-ZEPLIN collaboration, *First dark matter search results from the LUX-ZEPLIN (LZ) experiment*, *Physical Review Letters* **131** (2023) .

[5] PandaX-4T collaboration, *Dark matter search results from the PandaX-4T commissioning run*, *Physical Review Letters* **127** (2021) .

[6] M.L. Benabderrahmane et al., *Latest results from the XENON1T experiment*, *Journal of Physics: Conference Series* **1258** (2019) .

[7] SABRE South collaboration, *The SABRE South technical design report executive summary*, *Journal of Instrumentation* **20** (2025) T04001.

[8] DAMA/LIBRA collaboration, *Further results from DAMA/Libra-phase2 and perspectives*, *Nucl. Phys. Atom. Energy* **22** (2021) 329.

[9] SABRE collaboration, *The SABRE project and the SABRE proof-of-principle*, *The European Physical Journal C: Particles and Fields* **79** (2019) .

[10] J.H. Davis, *Fitting the annual modulation in DAMA with neutrons from muons and neutrinos*, *Physical Review Letters* **113** (2014) .

[11] SABRE collaboration, *Simulation and background characterisation of the SABRE South experiment*, *The European Physical Journal C: Particles and Fields* **83** (2023) .

[12] M. Antonello, I.J. Arnquist, E. Barberio, T. Baroncelli, J. Benziger, L.J. Bignell et al., *Characterization of SABRE crystal NaI-33 with direct underground counting*, *The European Physical Journal C: Particles and Fields* **81** (2021) .

[13] M.J. Zurowski, *Designing and Assessing Model Independent Tests of the DAMA Modulation*, Ph.D. thesis, The University of Melbourne, 2022.

[14] N. Carlin et al., *COSINE-100 Full Dataset Challenges the Annual Modulation Signal of DAMA/LIBRA*, 2409.13226.

[15] J. Amaré et al., *Towards a Robust Model-Independent Test of the DAMA/LIBRA Dark Matter Signal: ANAIS-112 Results with Six Years of Data*, *Phys. Rev. Lett.* **135** (2025) 051001 [2502.01542].

[16] DAMA/LIBRA collaboration, *First results from DAMA/LIBRA and the combined results with DAMA/NaI*, *The European Physical Journal C: Particles and Fields* **56** (2008) [0804.2741].

[17] J. Amare et al., *Analysis of backgrounds for the ANAIS-112 dark matter experiment*, *Eur. Phys. J. C* **79** (2019) 412 [1812.01377].

[18] P. Adhikari, G. Adhikari, E.B.D. Souza, N. Carlin, S. Choi, W.Q. Choi et al., *Background model for the NaI(Tl) crystals in COSINE-100*, *The European Physical Journal C* **78** (2018) .

[19] V. Niess, *The pumas library*, *Computer Physics Communications* **279** (2022) 108438.

[20] V. Niess, A. Barnoud, C. Cârloganu and E. Le Ménédeu, *Backward monte-carlo applied to muon transport*, *Computer Physics Communications* **229** (2018) 54.

[21] G. Adhikari et al., *An induced annual modulation signature in COSINE-100 data by DAMA/LIBRA's analysis method*, *Scientific Reports* **13** (2023) .

[22] D. Buttazzo et al., *Annual modulations from secular variations: Relaxing DAMA?*, *JHEP* **04** (2020) [2002.00459].