PROCEEDINGS OF SCIENCE

The SABRE South Experiment at the Stawell Underground Physics Laboratory

Peter Charles McNamara for the SABRE South Collaboration[a,b,*]

[a] *Department of Nuclear Physics and Accelerator Applications, The Australian National University, Canberra, ACT 2601, Australia*

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

E-mail: peter.mcnamara@anu.edu.au

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 (2900m 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. This proceeding will report on the design of SUPL and the construction and commissioning of SABRE South.

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*Speaker

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1. Introduction

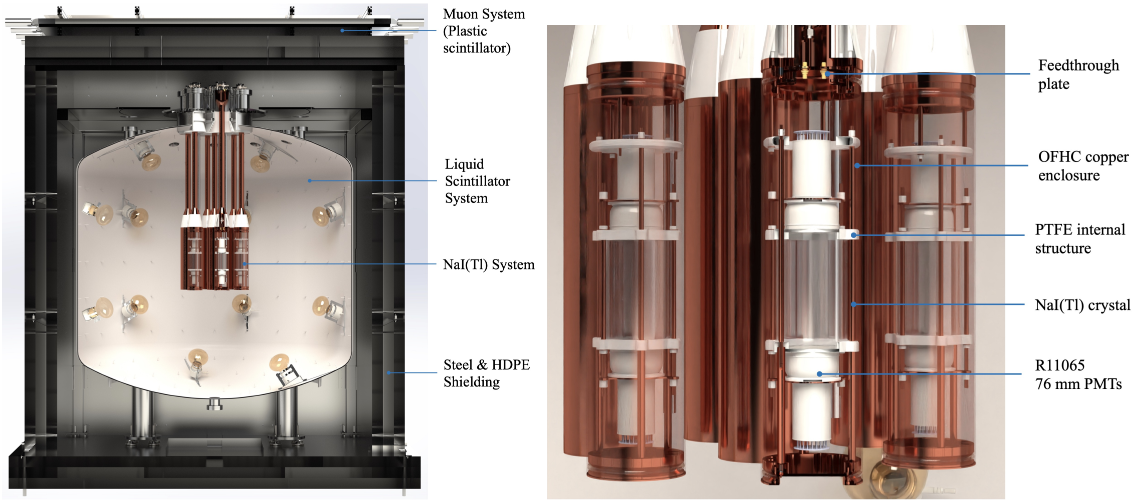
One of the most important unsolved problems in modern physics is the question of Dark Matter (DM) [1] and one promising candidate for DM are Weakly Interacting Massive Particles (WIMPs). These can be searched for using direct detection which attempts to observe the recoil of some target matter after a WIMP scatters off it. It is expected that the rate of WIMP-target interactions should have an annual modulation due to the changing velocity of the Earth as it orbits the Sun which itself orbits around the galactic centre. So far, only a single experiment in this area has claimed to observe a signal compatible with our expectations for DM: DAMA/LIBRA [2]. However this signal is in tension with the null results for a standard WIMP reported by many other experiments [3]. There have been some possible explanations for this tension, such as different target materials or possible seasonal effects. To resolve this tension the SABRE (Sodium iodide with Active Background REjection) collaboration aims to look for the signal reported by DAMA using the same target material (ultra-low background sodium-iodide crystals) and techniques. SABRE will have two detectors, SABRE North in the northern hemisphere at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy and SABRE South in the southern hemisphere at the Stawell Underground Physics Laboratory (SUPL), in Australia. The two detectors have a number of common features, each using the same detector module concept, the same crystal production and use common simulation, DAQ and data processing frameworks. The two detectors will differ in their shielding designs. SABRE North will use passive shielding due to the phase out of organic scintillators at LNGS. SABRE South will use liquid scintillator around the crystal modules which acts as both active and passive shielding as well as additional passive shielding. As the first experiment to be located at SUPL, the SABRE South liquid scintillator detector will be used for for in-situ evaluation and validation of the background in addition to background rejection and particle identification.

2. The SABRE South Experiment

The SABRE South experiment has three detector systems (Fig. 1a); the plastic scintillator muon detector, the liquid scintillator detector system and the NaI(Tl) crystal detector system.

The plastic scintillator muon detector uses eight 3 m long, 5 cm thick and 40 cm wide slabs of EJ200 for a total coverage of 9.6 m^2 and is located above the crystals outside the shielding. Each slab is instrumented by two Hamamatsu R13089 PMTs on each end which are attached via trapezoidal light guides. These PMTs are sampled by a CAEN 1743 digitiser at 3.2 GS/s allowing 5 cm position reconstruction along the length of each detector. These will primarily be used to identify and measure muons in the underground laboratory. This information will be combined with the other detectors for particle identification, to measure and characterise background flux and form part of the active veto with the liquid scintillator. These detectors will also be operated during construction of the experiment to obtain a measurement of the muon flux as a function of angle in SUPL.

The liquid scintillator is contained in a large vessel 2.8 m in diameter, housing 12 kL of linear alkyl benzene (sourced from JUNO) doped with PPO and Bis-MSB. This system uses eighteen 20.4 cm Hamamatsu R5912 PMTs which are submersed in the scintillator and attached to the walls of the vessel (Fig. 1a). Each PMT is sampled at 500 MS/s by CAEN 1730 digitisers which allow



(a) (b)

Figure 1: Renders of the SABRE Experiment showing (a) the main components of the full detector, and (b) a cutaway showing the main components of each crystal detector module.

for zero deadtime acquisition. This system is primarily designed to tag and veto intrinsic crystal backgrounds such as ^{40}K. It will also be used to measure background levels and background types near the target crystals and provide additional passive shielding. Based on preliminary optical simulations using Geant4 it is expected to have a light yield of about 0.12 photoelectrons/keV but is quite position dependent. With an energy threshold of 50 keV it can reduce intrinsic ^{40}K by 87% and the total crystal background reduces by 27% allowing a background of 0.72 cpd/kg/keV [4].

In total there are seven crystal detector modules (Fig. 1b), which can each host NaI(Tl) crystals 25 cm long and 5.5cm in radius. The crystals are wrapped in a reflective PTFE foil layer and held in place by PTFE crystal holders. Each crystal is instrumented by two Hamamatsu R11065 PMTs (7.6 cm in diameter) which are sampled at 500 MS/s by CAEN 1730 digitisers. The crystals are then enclosed in cylindrical oxygen-free high-thermal-conductivity copper (OFHC) enclosures flushed with high purity nitrogen.

In total the experiment uses 48 PMTs to collect signals. Before they are used in the experiment an extensive pre-characterisation program is underway to understand the response of these PMTs and their noise characteristics. This will be important for achieving reliable results and low thresholds, especially for the crystal PMTs which are intended to reach down to 1 keV.

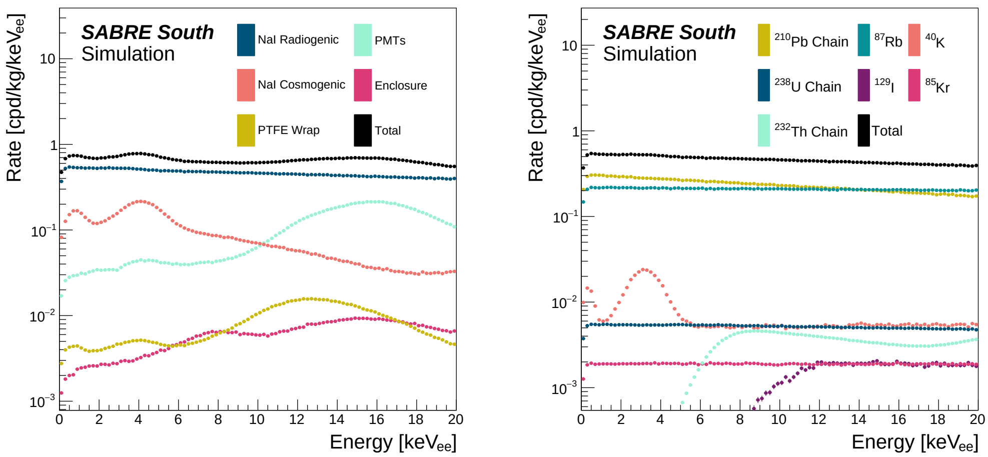
3. High Purity NaI(Tl) Crystals

The radiopurity of the NaI(Tl) crystals used in the experiment is of the utmost importance for achieving reliable results. As has been shown by other experiments [5–7] and in a dedicated simulation study of the backgrounds for SABRE South [4], the radioactive contamination in the crystals themselves forms a large fraction of the total background. By design 94% is expected to come from the crystals (Fig. 2a), with 72% from intrinsic sources (Fig. 2b), the most notable are ^{40}K and ^{210}Pb as the ^{87}Rb is an upper limit and expected to be much lower. Table 1 shows the

Experiment	^{nat}K [ppb]	^{238}U [ppt]	^{210}Pb [mBq/kg]	^{232}Th [ppb]	Active Mass [kg]
DAMA [2]	13	0.7 − 10	$(5-30)\times 10^{-3}$	0.5-7.5	250
ANAIS [9]	31	< 0.81	1.5	0.4	112
COSINE [10]	35	< 0.12	1 − 1.7	< 2.4	~60
SABRE [11]	4.3	0.4	0.5	0.2	~ 35 + 40 = 75 (goal)

Table 1: Purity levels and active mass of NaI(Tl) crystals of various experiments [12].

radioactive contamination levels in the crystals for various NaI(Tl) experiments. SABRE, through an R&D effort has developed some of the lowest background crystals in the world. Before producing the final crystals for the experiment some additional R&D is being conducted to further increase the purity by using zone refining [8] before the crystal growth. In this process furnaces slowly move over an ampoule of sodium iodide and over time impurities are pushed to one end, this has the potential to reduce ^{40}K, ^{87}Rb by a factor of 10 to 100 and ^{210}Pb by a factor of 2 [8].

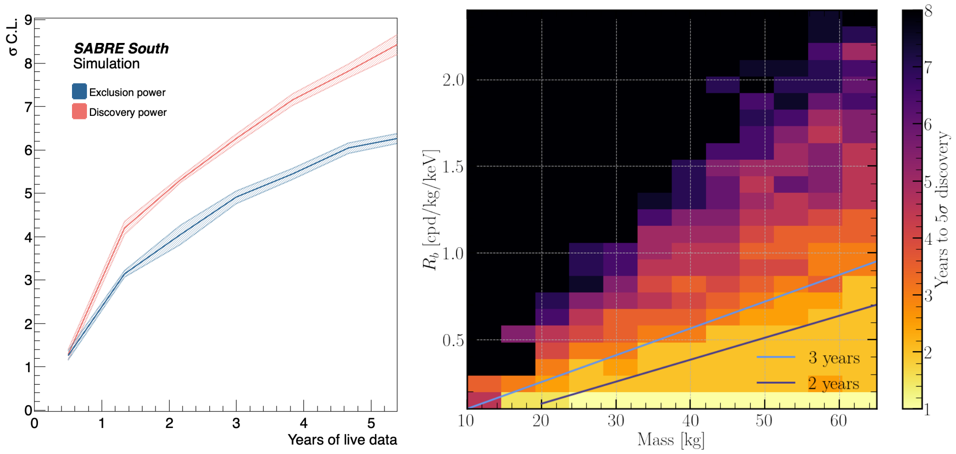


(a) (b)

Figure 2: (a) Total expected rate broken down by component. (b) Total expected rate for intrinsic contaminants in the crystal broken down by isotope.

4. Projected Sensitivity

The projected sensitivity of SABRE South using the background model from [4] which uses a crystal mass of 50 kg and and background of 0.72 cpd/kg/keV in the region of interest (1-6 keV) is shown in Figure 3a. Based on this SABRE South is expected to be able to confirm at 5σ or reject at 4σ the DAMA/LIBRA annual modulation result within 2.5 years. Figure 3b shows how the discovery power scales with different background (R_b) and target masses (M_E). Sensitivity in general is proportional to $\sqrt{M_E/R_b}$ [13] and so for similar performance with just 35kg of NaI(Tl), the background would need to reduce to about 0.5 cpd/kg/keV which is expected to be attainable using zone refining.

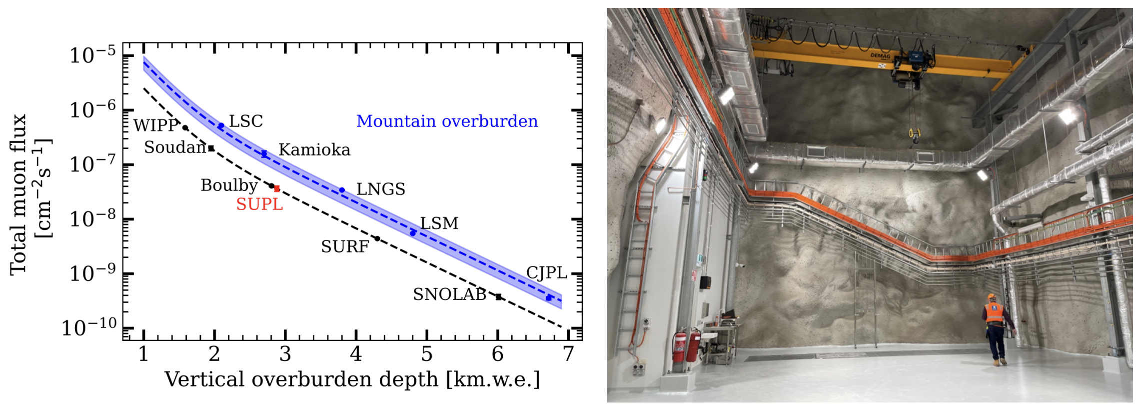


(a) (b)

Figure 3: (a) Exclusion and discovery power of SABRE South for a DAMA/LIBRA like signal with 50kg of crystal . (b) Plot showing how target mass and background rate change the sensitivity for discovery power.

5. The Stawell Underground Physics Laboratory

The SABRE South experiment will be located at the newly completed Stawell Underground Physics Laboratory (SUPL). SUPL has been constructed in a disused section of a gold-mine located in Stawell, 240 km west of Melbourne in Victoria, Australia. The laboratory was built at a depth of 1025 m or 2900 m water equivalent depth. It has a flat overburden and a muon flux similar to LNGS and Boulby (Fig 4a). The laboratory was completed in 2023 with background muon, gamma, and neutron measurements planned from 2023 to 2024, during the construction and commissioning of SABRE South.



(a) (b)

Figure 4: (a) Muon flux at SUPL and other underground laboratories. (b) Picture of SUPL where the SABRE South experiment will be located.

6. Conclusion

SABRE South as part of the SABRE collaboration aims to search for an annual modulation in ultra-pure NaI(Tl) crystals to provide a model independent test of DAMA/LIBRA. It is the first experiment to be located in SUPL which has now finished construction. SABRE South for a DAMA-like signal will be able to confirm it at 5σ or reject it at 4σ within 2.5 years with 50 kg target mass and a background rate of 0.72 cpd/kg/keV or 35 kg target mass and a background rate of 0.5 cpd/kg/keV which is expected to be attainable using zone refining. Construction and commissioning of SABRE South will occur 2023 to 2024.

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