Journal of Physics: Conference Series **2156** (2022) 012064 doi:10.1088/1742-6596/2156/1/012064

SABRE South at the Stawell Underground Physics Laboratory

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Abstract. The SABRE (Sodium-iodide with Active Background REjection) experiments aim to detect an annual rate modulation from dark matter interactions in ultra-high purity NaI(Tl) crystals. The SABRE South experiment is located at the Stawell Underground Physics Laboratory (SUPL), Australia, the first deep underground laboratory in the southern hemisphere, due to be completed in late 2021. SABRE South is designed to disentangle seasonal or site-related effects from the dark matter-like modulated signal first observed by DAMA/LIBRA in the Northern Hemisphere. It is a partner to the SABRE North effort at the Gran Sasso National Laboratory (LNGS). SABRE South is instrumented with ultra-high purity NaI(Tl) crystals immersed in a linear alkylbenzene based liquid scintillator veto, further surrounded by passive steel and polyethylene shielding and a plastic scintillator muon veto. The SABRE South experiment is under construction, and will be commissioned in early 2022.

In this article we present the final design of SABRE South, the status of its construction, and its expected sensitivity to a DAMA/LIBRA like modulation. We will also present a brief report on the status of SUPL.

1. Introduction

The annual modulation of the WIMP-nucleon interaction rate is a unique model independent signal for WIMP dark matter, caused by the relative motion of the earth through the galactic halo. The DAMA experiments have a 20 year record of a WIMP-compatible modulating signal for recoil energies of 1-6 keV with a combined significance of 12.9σ [1]. This result is in tension for a spin-independent WIMP with null results from large noble gas detectors. This necessitates replication studies by experiments utilising the same target with a comparable background.

The SABRE (Sodium-iodide with Active Background REjection) experiment is an independent replication of the DAMA experiment. One of the key factors is the use of a southern hemisphere detector, which allows seasonal effects to be disentangled from the claimed WIMP modulation signal by exploiting the seasonal shift. The SABRE South detector will be constructed and commissioned in 2022 in the newly constructed Stawell Underground Physics Laboratory, which is the southern hemisphere's first deep underground lab dedicated to low-background physics.

2. The SABRE South Detector

The SABRE South detector will consist of an array of ultra high purity NaI(Tl) crystals immersed within a liquid scintillator veto that provides 4π coverage. This is in turn located

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within passive shielding provided by low radioactivity steel and polyethylene. A layer of muon detectors is operated on top of the passive shielding to provide additional tagging of cosmogenic muons.

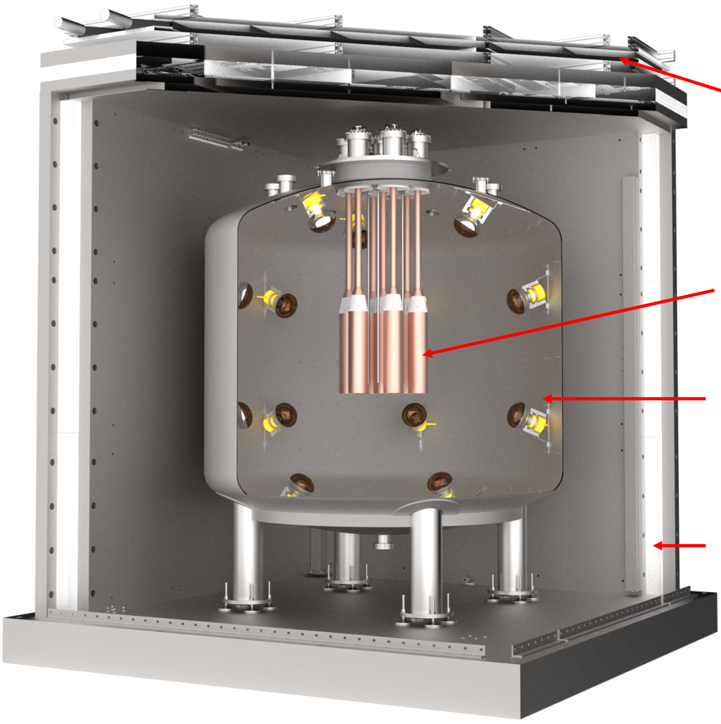

Figure 1. The SABRE South detector with NaI(Tl) crystal array, liquid scintillator veto, passive shielding and muon veto. The NaI(Tl) crystal array consists of seven high purity NaI(Tl) crystals directly coupled to two Hamamatsu R11065 PMTs within a low background copper enclosure. The liquid scintillator veto uses 12,000 L of LAB with PPO and Bis-MSB with 18 R5912 oil-proof PMTs.

The NaI(Tl) crystal array consists of seven crystals directly coupled to two 76 mm Hamamatsu R11065 photomultipliers (PMTs) with a quantum efficiency in excess of 30%. The crystals and PMTs are sealed inside vacuum-tight enclosures made from ultra low background oxygen-free copper and are fluxed with dry nitrogen gas. The enclosures are inserted directly into the liquid scintillator to minimise the amount of material between the crystal and active veto. The active veto systems consists of 12,000 litres of Linear Alkylbenzene (LAB) scintillator with PPO and Bis-MSB added as fluorophores. This is instrumented with 18 204 mm Hamamatsu R5912 PMTs mounted on the walls of the veto vessel. These PMTs have an oil proof assembly allowing them to be fully immersed in the liquid scintillator. The internal surface of the veto vessel will be coated with a diffuse reflecting PET film to increase the photon detection efficiency of scintillation light. The active veto system has been designed to veto the gamma ray produced by intrinsic potassium-40 decays within the NaI(Tl) crystals with an efficiency greater than 85%. The muon veto system consists of eight panels of 5 cm thick EJ-200 organic scintillator measuring 0.4 m by 3 m, providing a total of 9.6 m^2 of coverage centred over the NaI(Tl) crystal array. The EJ-200 scintillator panels are coupled at each end to a light guide and a high-speed PMT, read out at 3.2 GS/s. This provides a longitudinal position resolution for downward travelling muons of approximately 5 cm. These detectors are crucial to provide measurements of the seasonal muon modulation at the Stawell Underground Physics Laboratory.

The experiment will operate with triggers sensitive to single photons in both the NaI(Tl) array and liquid scintillator veto. This will enable a software threshold of approximately 1 keV for the NaI(Tl) crystal detectors, and a sensitivity to energy depositions of approximately 50 - 100 keV in the liquid scintillator veto. Both the NaI(Tl) and veto PMTs are readout at 500 MS/s using CAEN digitisers with a configurable FPGA trigger. The resulting waveforms will be transferred via optical fibre to a local data acquisition server for initial processing, before being transferred to the University of Melbourne for permanent storage.

3. Status

3.1. Na Quenching Factor

Measurements of the Na quenching factor for nuclear recoils in NaI(Tl) were performed using the Heavy Ion Accelerator Facility at the Australian National University. The quenching factor was determined using a recoil spectrum fitting technique based on Markov chain Monte Carlo simulation. Further details on the method and results can be found in Ref. [2]. We are currently repeating these measurements using off-cuts from a ultra-low background crystal grown with Merck Astro-grade NaI powder.

3.2. Photomultiplier Characterisation

To operate with a 1 keV threshold in the crystal detectors, SABRE South requires precise characterisation of its photomultipliers. To do this we have developed a single photon measurement system using a Hamamatsu PLP-10 picosecond pulsed laser and high-speed waveform sampling readout electronics (500 MS/s). This apparatus allows for precise measurements of the single photon response and timing, as well as the absolute quantum efficiency of each photomultiplier. We have measured the dark noise rate and distributions as a function of detector voltage and temperature. This process is now being prepared for the bulk characterisation of all liquid scintillator and NaI(Tl) photomultipliers. Results from these tests are being used to develop noise rejection tools that are effective at the 1 keV energy scale in the NaI(Tl) detectors.

3.3. Construction

The SABRE South experiment is scheduled to be commissioned in 2022 in the Stawell Underground Physics Laboratory. A volume of 12,000 L of LAB liquid scintillator base has been sourced from Nanjing using the same supplier as JUNO [3], with a photon attenuation length greater than 20 m, and ^{238}U, ^{232}Th, and ^{40}K content below 10^{-17} g/g. The veto vessel has been constructed and is currently being prepared for Lumirror PET film and PMT bracket mounting. The full compliment of crystal PMTs has been sourced from Hamamatsu and are currently being prepared for bulk characterisation, while the PMTs used in the veto are due soon.

4. Projected Sensitivity

The sensitivity of SABRE South has been estimated in Ref. [4]. With 50 kg of NaI(Tl) and a projected background of 0.36 cpd/kg/keV [5] SABRE South will have a 5σ discovery power to a DAMA like signal with two years of run time, and a 5σ exclusion power within 5 years. Figures 2 and 3 show the evolution of discovery and exclusion power of SABRE South as a function of experiment run time. The projected sensitivities of ANAIS and COSINE are determined using information contained in Refs. [6] and [7].

5. Stawell Underground Physics Laboratory

The Stawell Underground Physics Laboratory (SUPL) is the southern hemisphere's first deep underground laboratory for low background physics. Located in the Stawell Gold Mine, an active

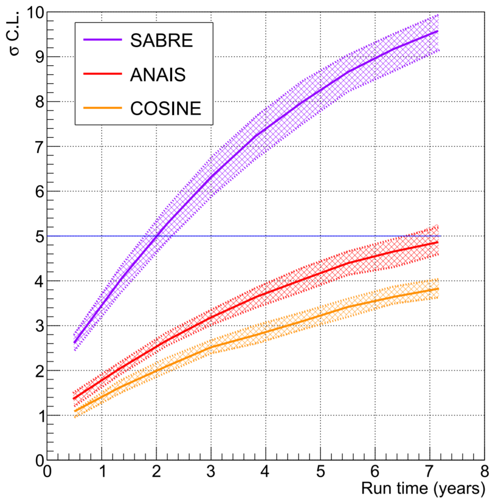

Figure 2. Discovery power of a DAMA like modulation signal as a function of exposure time. [4]

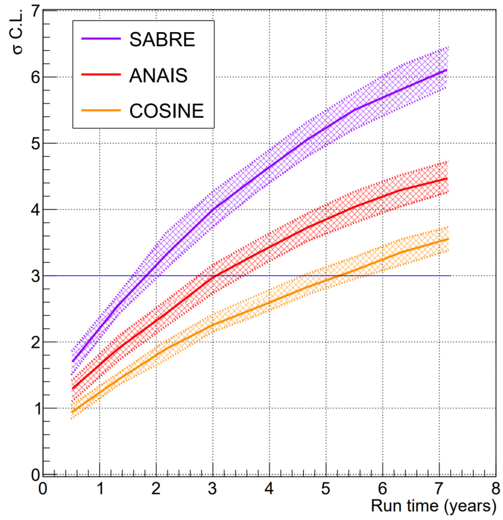

Figure 3. Exclusion power of a DAMA like modulation signal as a function of exposure time.[4]

mine located 240 km north west of Melbourne. The laboratory is 1024 m below ground with a flat over burden. This provides 2.88 km of water equivalent shielding resulting in a measured muon flux of $(3.65 \pm 0.41) \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [8].

SUPL consists of a 300 m^2 experimental hall with a minimum height of 12 m which is operated as a radon suppressed clean room. There will be additional facilities located on site including high purity germanium counting detectors.

The laboratory is scheduled for completion by the end of 2021, with preparation underway for detailed background measurements in the main cavern. The muon flux and angular spectrum will be measured with the SABRE South muon veto operated in a telescope configuration. The neutron energy spectrum will be measured using a series of Bonner spheres and a ^{3}He detector.

6. Conclusion

SABRE South will be assembled and commissioned in 2022 in the newly constructed Stawell Underground Physics Laboratory. With 50 kg of NaI(Tl) at our expected background we expect to reach a 5σ discovery sensitivity to a DAMA-like signal within two years of operation.

Acknowledgments

This research was supported (partially or fully) by the Australian Government through the Australian Research Council Centre of Excellence for Dark Matter Particle Physics CE200100008, and grant numbers DP190103123, LE190100196, LE170100162, LE160100080, LP150100705. The Stawell Underground Physics Laboratory construction and operation is funded by the Victorian State Government and the Australian Federal Government. The low-background NaI crystal was provided by Radiation Monitoring Devices, Inc., Massachusetts, USA, under the support of the US Department of Energy, Office of High Energy Physics, grant number DE-SC0013760.

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