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The SABRE experiment for dark matter search

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The SABRE (Sodium-iodide with Active Background REjection) experiment is a new detector based on NaI(Tl) scintillating crystals for the dark matter detection through the annual modulation. With ultra-pure crystals and an active veto system, based on liquid scintillator surrounding the crystal array, SABRE will reach unprecedented low background and the highest sensitivity among the present NaI(Tl) experiments. Moreover SABRE will be the first dark matter search with twin detectors located in the North and South hemispheres, in Gran Sasso National Laboratories (LNGS), Italy, and Stawell Underground Laboratories (SUPL), Australia, respectively. The double location will help to quantify possible seasonal effects, and is a unique feature to identify a modulation of dark matter origins. SABRE is presently in the Proof-of-Principle (PoP) phase, with the goal to measure the crystal intrinsic and cosmogenic backgrounds of one 5 kg crystal and the active veto efficiency. We have performed a full geometry Monte Carlo simulation in order to evaluate the background contributions in the two distinct operation modes foreseen for the PoP: the potassium Measurement Mode (KMM) and the Dark Matter Measurement Mode (DMM), where the liquid scintillator detector is used in coincidence or anti-coincidence with the crystal, respectively. This paper presents the results of a detailed background simulation and the expected sensitivity for the SABRE full scale experiment.

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In the last decades, many direct detection experiments have been searching for dark matter candidates, in particular Weakly Interactive Massive Particles (WIMPs) [1]. Assuming that dark matter is distributed in halos around galaxies, a flux of WIMPs is expected to pass through the solar system. Since the Earth is moving around Sun, an Earth-based experiment would see an annually modulated flux [2]. The DAMA experiment (short for DAMA/NaI and DAMA/LIBRA), located in the LNGS, has observed a clear modulation signal in NaI(Tl) crystals in about 20 years of data taking. Combining the DAMA/NaI, DAMA/LIBRA Phase-1 [3] and the recently released Phase-2 results [4], DAMA observes a modulation signal of 12.9 σ significance that meets all the requirements of a model-independent dark matter annual modulation in the 1–6 keV energy range. Results of other experiments using different target material [5], if interpreted in the hypothesis of WIMP galactic halo and WIMP nuclear scattering, seem to exclude the dark matter interpretation of DAMA results. However a model-independent comparison is only possible between experiment using the same material, since the nature of dark matter interaction with standard matter is unknown.

SABRE enters in this scenario as a new ultra-pure sodium-iodide based detector, capable to test the DAMA measurement with high sensitivity.

A crucial part of the SABRE project is the development of high-purity Na(Tl) crystals, since the most important background for this experiment is due to intrinsic radioactive impurities. In a 2-kg test crystal, produced for SABRE by Princeton University and Radiation Monitoring Devices Inc. (RMD), the measured level of ^{nat}K is 10 ppb, while U and Th are below the ICP-MS detection limit of 1 ppt [6]. As a comparison, DAMA, that uses the purest NaI(Tl) crystals so far, reports an average of 13 ppb ^{nat}K in their crystal, ^{238}U and ^{232}Th content below 0.01 ppb [7].

A feature of the SABRE design is the use of an active veto system, consisting in a liquid scintillator surrounding the crystal array, instrumented with PMTs. Background events from both intrinsic and external sources are likely to deposit energy also in the veto or the adjacent crystals, while a WIMP signal is expected to give a low energy release in a single detector. For instance, the dangerous 3 keV signal following the electron capture of ^{40}K in the crystal can be rejected by detecting the coincident 1.46 MeV gamma signal in the adjacent crystals or in the liquid scintillator. The veto rejection efficiency predicted for ^{40}K in SABRE crystals is about 84%.

The double location is a unique characteristics of SABRE experiment. The SABRE twin detectors will be placed at LNGS, Italy, and at SUPL in Australia. SUPL will be the first underground laboratory in the southern hemisphere and is located 240 km north-west of Melbourne in a section of an active gold mine. The chosen site is 1025 m deep, corresponding to a $\sim$3000 m water equivalent depth, similar to LNGS. The annual modulation of the experimental rate induced by dark matter interaction is expected to have the same phase in both hemispheres, given its galactic origin. In contrast, an annual modulation of the rate due to seasonal or site effects would be characterized by a different phase and amplitude in the two detectors.

The SABRE experiment is now in the Proof-of-Principle (PoP) phase, with the goal to characterize the crystals in term of intrinsic and cosmogenic background, scintillation and optical properties, and to measure the veto efficiency.

The PoP consists of a single NaI(Tl) cylindrical crystal, of about 4 inches diameter and 5 kg mass. Two high quantum efficiency, low radioactivity, Hamamatsu R11065-20 PMTs of 3 inches diameter are directly coupled with each of the two flat faces of the cylindrical crystal.The detector module is sealed in a high-purity and light-tight copper enclosure fluxed with dry and clean nitrogen to avoid humidity and radon. It is inserted in the center of a cylindrical vessel (1.3 m diameter $\times$1.5 m length) filled with $\sim$ 2 tons of distilled pseudocumene, doped with 3 g/l of PPO and instrumented with ten 8-inch Hamamatsu R5912-100 PMTs.

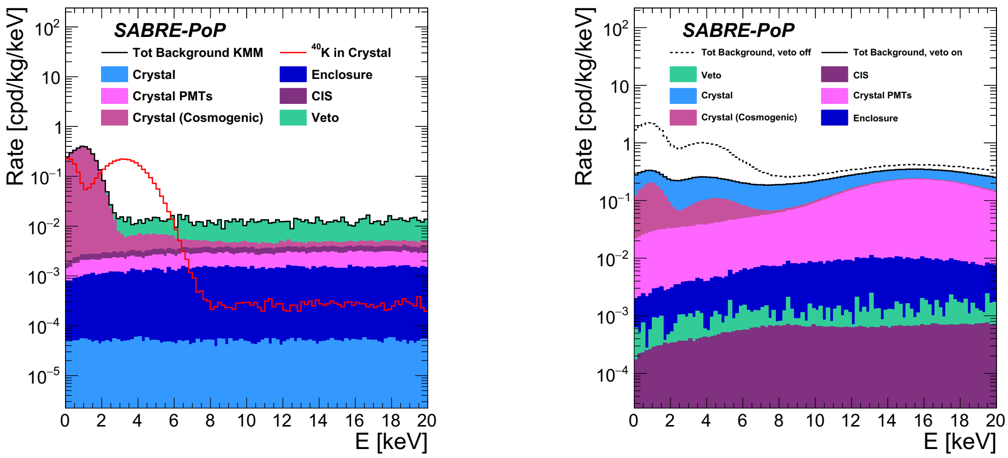
To allow the insertion of the detector module, a 2 mm thick copper tube is connected to the top cover plate of the vessel and provides a dry volume inside the veto tank.

To further shield the setup from external radiation, the vessel is surrounded by several layers of passive material: from inside out, about 40 cm of polyethylene on all sides and basement, a 2 cm steel plate at the top, an additional layer of 15 cm of lead, and water tanks of 80(91) cm thickness on top (sides).

The technical design of the SABRE–PoP is described in detail in [8].

A Geant4 [9] Monte Carlo simulation has been performed to evaluate the background of the PoP setup [6]. It has been used as a guide tool during the design phase, and will be of crucial importance to understand the measured background, once PoP data will be available.

We evaluated the background in the two distinct operation modes foreseen for the PoP: the potassium Measurement Mode (KMM) and the Dark Matter Measurement Mode (DMM), where the liquid scintillator detector is used in coincidence or anti-coincidence with the crystal, respectively.



(a) (b)

Figure 1: Background from all SABRE-PoP setup components in a $(0-20)$ keV region in KMM (left) and in DMM (right).

The KMM will be used to measure the ^{40}K activity in the crystal, which is a significant background contribution to the energy spectrum in the region of interest for a dark matter search. In this mode the liquid scintillator (LS) is used in coincidence with the signal in the crystal, selecting events with an energy deposit between 1.28 and 1.64 MeV (2σ interval around the 1.46 MeV γ emitted in the ^{40}K electron capture decay). From results summarized in Fig. 1a, we expect that 10 ppb of ^{nat}K can be measured with $\sim$1 ppb precision in about two months of data taking.

We estimate the background level attainable by the PoP in DMM by looking at energy depositions from 2 to 6 keV in the crystal, in anti-coincidence with the veto (LS threshold 100 keV). The predicted background level for the PoP setup is 0.24 cpd/keV/kg (see Fig. 1b).

Assuming the background spectrum in DMM obtained from the simulation and without any assumption on the dark matter model, with 50 kg $\times$ 3 years exposure, SABRE will be able to confirm (exclude) DAMA modulation at the level of 6 (5)σ significance.

We have also evaluated the sensitivity to spin-independent (SI) WIMP nuclear scattering [10]. The quenching factor of nuclear recoils on sodium and iodine are taken from [11] and [12] respectively. The detection efficiency and resolution were set at the values reported by the DAMA collaboration [7] for their detectors. Result is shown in Fig. 2. The uncertainty bands at 1 and 3σ (green and yellow respectively) take into account the systematic uncertainties on background, efficiency, resolution and quenching factors.

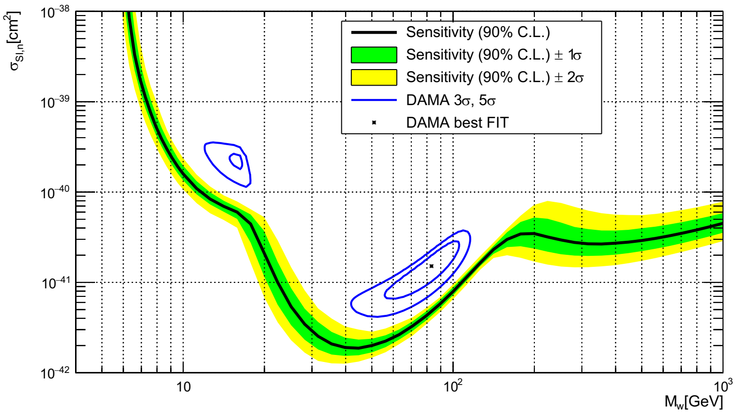


Figure 2: SABRE sensitivity to WIMP-nuclear SI scattering with uncertainty bands. The blue curves represent the 3 and 5 σ confidence intervals of DAMA Phase-1 results interpreted in the same framework.

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