SABRE: Dark matter annual Modulation Detection in the Northern and Southern Hemisphere

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Abstract

SABRE (Sodium-iodide with Active Background REjection) is a new NaI(Tl) experiment designed to search for galactic Dark Matter through the annual modulation signature. SABRE will consist of highly pure NaI(Tl) crystals operated in an active liquid scintillator veto. The SABRE experiment will follow a two-phase approach. In the first phase, one high-purity NaI(Tl) crystal will be operated at LNGS in an active liquid scintillator veto with the goal of demonstrating backgrounds low enough for a sensitive test of the DAMA/LIBRA result. An unprecedented radio-purity for both the NaI powder and the crystal growth will be needed to achieve this goal. The second phase will consist in building two high-purity NaI(Tl) detector arrays, with a total mass of about 50 kg each, located at LNGS and in the Stawell Gold Mine in Australia. The operation of twin full-scale experiments in both the northern and the southern hemisphere will strengthen the reliability of the result against any possible seasonal systematic effect.

Keywords: Dark Matter direct detection, Dark Matter annual modulation, NaI(Tl)crystals

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1. Introduction

A huge number of experiments worldwide have been searching for many years for direct signals of Dark Matter interactions. In the most common framework

12 of Dark Matter being in form of WIMPs (Weakly Interacting Massive Parti-
 13 cle), distributed uniformly in the Galactic halo, experiments search for nuclear
 14 recoils produced by WIMP interactions in an underground detector. A Dark
 15 Matter signal on an Earth-based detector is expected to modulate yearly due
 16 to the change of the Earth's speed relative to the galactic halo reference frame.
 17 The long standing result from the DAMA/LIBRA [1] experiment at the Gran
 18 Sasso National Laboratory (LNGS) is consistent with this scenario, while a con-
 19 firmation of this result by an independent experiment is still missing. In fact, no
 20 other experiment so far using NaI(Tl) scintillating crystals as target, has stud-
 21 ied the annual modulation effect with similar sensitivity to DAMA/LIBRA. At
 22 the same time, when interpreted in the standard WIMP framework, the results
 23 from DAMA/LIBRA are in tension with other results from experiments using
 24 different targets[2, 3, 4, 5].
 25 SABRE [6, 7] (Sodium-iodide with Active Background REjection) is designed
 26 to be such an experiment, based on NaI(Tl) scintillating crystals and focused on
 27 the achievement of a very low background via crystal purity and active rejection
 28 through liquid scintillator veto. The SABRE project foresees the installation of
 29 twin detectors underground at LNGS (Italy) and Stawell gold mine (a future
 30 underground site in Australia), thus providing an effective way to disentangle
 31 possible seasonal modulations, that in the southern hemisphere have opposite
 32 phase.

33 **2. The SABRE experiment**

34 The SABRE experiment seeks to improve the performances attained by the
 35 DAMA/LIBRA array by focusing the effort on the development of NaI(Tl)
 36 crystals with an unprecedented radio-purity and on the operation of the scintil-
 37 lating crystals in a liquid scintillator (LS) veto plus a passive shielding, with
 38 the goal of achieving lower backgrounds and lower energy thresholds than those
 39 of DAMA/LIBRA. Moreover, as we mentioned above, exploiting twin detectors
 40 in the northern and southern hemisphere will serve as a powerful tests against

41 environmental backgrounds.

42 *High-purity NaI(Tl) crystals.* In Dark Matter experiments such as SABRE, the
 43 reduction of the background in the energy region of interest (ROI), that is from
 44 threshold to a few keV, plays a key role. For this reason, the success of the
 45 SABRE project depends crucially on the radio-purity of the crystals. This pro-
 46 cess starts with the creation of high purity powder, which is then transformed
 47 into high purity crystals by an ultra-clean crystal growing procedure. All in-
 48 volved materials, especially those in contact with the powder or the final crystal,
 49 must be carefully selected and cleaned with a dedicated procedure meticulously
 50 developed. A key for the successful establishment of the entire process is the
 51 development of techniques to measure the impurities in the powder and in the
 52 crystal with high sensitivity prior to deployment in the experimental apparatus.
 53 The development of ultra-high purity NaI powder was accomplished through an
 54 R&D project between Princeton University and the industrial partner Sigma-
 55 Aldrich (SA). As a result of this effort, SA produced the so-called Astrograde
 56 powder with K levels as low as 3.5 ppb. Table 1 shows inductively coupled
 57 plasma mass spectroscopy (ICP-MS) results (confirmed by gamma counting)
 58 for the most interesting impurities K, Rb, U, and Th for the Astrograde powder
 59 in comparison with DAMA’s powder and crystal purity.

Table 1: Purity levels of Sigma Aldrich’s Astrograde NaI powder in comparison with DAMA’s powder and crystal purity [8].

Element	Sigma- Aldrich [ppb]	DAMA Powder [ppb]	DAMA Crystal [ppb]
K	3.5 (18)*	100	~ 13
Rb	0.2	n.a.	< 0.35
U	$< 1.7 (< 10^{-3})^{**}$	~ 0.02	$0.5 - 7.5 \times 10^{-3}$
Th	$< 0.5 (< 10^{-3})^{**}$	~ 0.02	$0.7 - 10 \times 10^{-3}$

* Independent measurement ** Preliminary measurement at PNNL; full validation needed.

60 The values show that the Astrograde powder has significantly lower impu-
 61 rity levels compared to DAMA's powder and similar levels as DAMA's crystals.
 62 We are currently working on methods to further purify the NaI prior to crystal
 63 growth. As the next step we are developing together with Radiation Monitoring
 64 Devices (RMD) an ultra-clean crystal growth procedure. To grow our crystals
 65 we are using the vertical Bridgman-Stockbarger technique[9], where a crucible
 66 is typically placed inside a sealed ampoule. Small test growths using Astro-
 67 grade powder and different materials for the crucible and ampoule were done
 68 to determine the radioactive contamination of the crystal during the growth via
 69 ICP-MS. The optimum crucible-ampoule combination together with a precision
 70 cleaning showed no increase of the impurity levels inside the crystal. Measure-
 71 ments performed in January 2016, on a 2-kg NaI(Tl) crystal grown by RMD out
 72 of SA Astrograde powder, demonstrate potassium level at 9 ppb and rubidium
 73 level lower than 0.1 ppb. The established procedure is being scaled up to larger
 74 crystal masses. The final goal is to grow 5 kg high-purity crystals.

75 *Detector module and LS Veto.* NaI(Tl) scintillating crystals of the desired ra-
 76 diopurity will be coupled directly with two 3" photomultiplier tubes (PMTs).
 77 The PMTs must feature both a high quantum efficiency and a background as
 78 low as possible. Our collaboration with Hamamatsu Japan has already resulted
 79 in PMTs with a low radioactivity of 3 mBq/PMT U, 0.5 mBq/PMT Th, Co
 80 and 2 mBq/PMT K[10], the R11065-20 series. Additional improvements are
 81 currently under development. They are expected to further reduce the total
 82 radioactivity by a factor of 10 and might also improve the overall stability of
 83 the PMTs. The crystal and PMTs will then be packaged in a low radioactivity,
 84 air- and light tight, high purity copper enclosure, to form the so-called SABRE
 85 detector module.

86 The detector module will be deployed into a 1.4 m diameter, 1.5m length cylin-
 87 drical, low-radioactivity stainless-steel vessel. The vessel, filled with 2 tons
 88 of liquid scintillator (pseudocumene doped with PPO) and equipped with 10
 89 Hamamatsu R5912 PMTs, will act as an active veto. The vessel's inner surface

Figure 1: Schematic drawing of the SABRE PoP setup: the detector module (also shown enlarged on the left picture) will be placed inside the liquid scintillator veto, a stainless steel vessel equipped with PMTs and filled with pseudocumene (photograph on the right).

is coated with ETFE to prevent scintillator degradation due to contact with the stainless steel. The predicted light yield of the liquid scintillator veto is 0.22 photoelectrons/keVee with a Lumirror liner on the inner surface [11]. The veto vessel will be further shielded from the external environmental background by an hybrid passive shield made of lead and polyethylene for the basement and water tanks on the side and top.

One of the main features of the LS veto is to effectively reduce the background from ^{40}K trace contamination in the crystal. The background due to this isotope of potassium is particularly dangerous for Dark Matter searches since one of its decay channels emits a 3 keV X-ray (or Auger electron), accompanied by a 1.46 MeV gamma. If the high energy gamma goes undetected in the crystal, the 3 keV energy deposition results in a peak right in the region of interest around 2-6 keV. The signal produced by the 1.46 MeV gamma in the LS veto can be used to identify and ultimately veto these events, as can be seen in Figure 2.

The SABRE phased strategy. The development of SABRE is expected to follow a two phase program. The first phase (SABRE Proof of Principle or PoP) aims at developing radio-pure NaI(Tl) crystals and testing them in an active veto detector at LNGS. The second phase foresees the construction and operation of two arrays of these low background crystal detectors to perform a large-scale

Figure 2: Montecarlo simulation of the ^{40}K background rejection at low energy obtained through the LS veto in the SABRE PoP setup.

test of the DAMA signal. Estimations of the SABRE sensitivity, assuming the scintillating NaI(Tl) crystals have the same purity observed in the Astrograde powder and that the external radiation can be effectively shielded, predict that, with a 50 kg total mass, SABRE will be able to confirm the DAMA/LIBRA result at a 4σ level in a 3-year run.

To strengthen the reliability of the result against possible seasonal systematic effects, we currently plan to operate twin full-scale experiments, one in the northern hemisphere at LNGS, one in the southern hemisphere inside the Stawell gold mine in Victoria, Australia, which is being converted into an underground laboratory (SUPL). The Stawell gold mine is located in the State of Victoria, about 240 km west of Melbourne. It is an operational decline mine, with flat surface and 1.6 km maximum depth. The caverns can be reached by car/truck. The chosen lab site is a cavern 1 km depth, corresponding to 3.1 km w. e. (basalt density of the mine $\sim 2.86 \text{ t/m}^3$). The Laboratory was proposed in 2014. Since then, the funding was secured and the design was prepared and it's currently being reviewed. The construction will start soon, with the goal of having the laboratory operational in 2017.

127 **3. The SABRE Proof of Principle**

128 SABRE is currently in a Proof-of-Principle phase which, as mentioned above,
129 will be conducted at LNGS with the aim to asses the radiopurity of the NaI(Tl)
130 crystals grown for SABRE by direct gamma counting, and show that this is
131 compliant to the requirements needed to the full SABRE project. This is es-
132 pecially important for isotopes where the ICP-MS is not sensitive enough. On
133 the other hand the PoP will demonstrate the feasibility to operate high purity
134 NaI(Tl) crystals inside a liquid scintillator veto and test the veto efficiency and
135 its background reduction capability. The operation of high purity crystals inside
136 the liquid scintillator veto will allow us to study in details the background of
137 the PoP setup, namely:

- 138 • intrinsic contaminations of the crystals, including cosmogenic activation;
- 139 • background from other components of the setup outside the crystals, that
140 is PMTs, enclosure, liquid scintillator, etc;
- 141 • background from external sources;

142 A full study of the background model will be performed by means of GEANT4 [12]
143 Monte Carlo simulations. The SABRE PoP setup will be installed inside Hall
144 B at LNGS. It will be surrounded by an hybrid shielding made out of lead
145 and polyethylene on the bottom and water tanks on the side and top. Most
146 components are already available, commissioning of the veto vessel started at
147 Princeton University, and preparations at LNGS are in progress.

148 **4. Conclusions**

149 The long standing result from the DAMA/LIBRA experiment at the Gran
150 Sasso National Laboratory (LNGS) is consistent with the presence of an an-
151 nual modulation with the predicted characteristics of a Dark Matter induced
152 effect, however a confirmation of this result by an independent experiment using
153 NaI(Tl) scintillating crystals as target is missing.

SABRE[6] (Sodium-iodide with Active Background REjection) is designed to be such an experiment, based on NaI(Tl) scintillating crystals and focused on the achievement of a very low background via crystal purity and active rejection through liquid scintillator veto. The SABRE Proof of Principle phase has started and the PoP setup is going to be assembled soon at LNGS. In addition, the full SABRE project foresees the installation of twin detectors both at LNGS and in the Stawell gold mine (a future underground site in Australia), thus providing an effective way to disentangle possible seasonal modulations, that in the southern hemisphere have opposite phase.

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