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Status and prospects of SABRE North

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SABRE is an experiment to search for galactic dark matter (DM) through the annual modulation effect and to perform a model-independent test of the long-standing DAMA result. The ambitious program of SABRE foresees two detectors in underground locations in the two Earth's hemispheres: SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy and SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia. We present the status and prospects of SABRE North activities, namely the characterization of a low background NaI(Tl) crystal in two different setups at LNGS. The former Proof-of-Principle (PoP) detector was equipped with a liquid scintillator (LS) veto and collected data for about one month. The latter, called PoP-dry setup, featured a purely passive shielding and collected data for almost one year. The average background in the energy region of interest (1-6 keV) for DM search was 1.20 ± 0.05 and 1.39 ± 0.02 counts/day/kg/keV within the PoP and the PoP-dry setup, respectively. The main features of the background in the crystal have been addressed with both the PoP and the PoP-dry setup. Upcoming activities and future perspectives of SABRE North are discussed, together with a brief mention of the status of SABRE South.

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1. Introduction

The SABRE (Sodium-iodide with Active Background REjection) project was proposed to carry out a model-independent search of dark matter via the annual modulation signature, with an unprecedented sensitivity, in order to confirm or refute the DAMA/LIBRA claim [1]. To this aim, SABRE plans to develop and operate ultra-low background scintillating detectors consisting of NaI(Tl) crystals, the same target material as DAMA/LIBRA. A further ambitious goal of SABRE is to deploy two independent NaI(Tl) crystal arrays in the northern (SABRE North) and southern (SABRE South) hemispheres. This will allow to identify possible contributions to the annual modulation from seasonal or site-related effects. SABRE North aims to reach a background rate well below the DAMA/LIBRA level, namely of the order of 0.3-0.5 counts/day/kg/keV (cpd/kg/keV) in the 1-6 keV energy region. This background goal is very ambitious, also considering that currently running experiments using NaI target, that is ANAIS-112 and COSINE-100 [1–3], have not yet reached the ultra-low background and sensitivity achieved by DAMA.

As a large fraction of the background in the ROI for DM search comes from residual radioactive contaminants in the crystal themselves, especially ^{40}K and ^{210}Pb, the development of ultra-high purity NaI(Tl) crystals is the path followed by the SABRE collaboration to achieve the ultimate verification of the DAMA result, in about three years of data-taking and with a total mass of just a fraction of the present generation experiments. The best performing and radio-pure crystal produced as a result of the long SABRE R&D was carefully characterized inside both the SABRE PoP detector [4] in 2020 and the SABRE PoP-dry detector [5] in 2021 at LNGS.

2. The PoP and PoP-dry experimental tests

The main R&D effort of SABRE was focused on the development of high purity NaI(Tl) scintillating crystals. The collaboration with industrial partners Sigma Aldrich (now Merck) for the ultra-high purity NaI powder (Astro Grade) and Radiation Monitoring Devices, Inc (RMD) for the clean growth procedure, led to the production of a 3.4-kg crystal called NaI-33. NaI-33 was characterized within two different detectors at LNGS.

The SABRE PoP took data at LNGS between July and September 2020. The goal was to assess the radio-purity of SABRE crystals and test the performances of an active veto, that at the time was part of the detector's design. The PoP collected data for a total exposure of 90 kg×days and, despite the short time, it achieved several important results. The measurement of potassium content in the crystal by direct counting, exploiting coincidences between the crystal and the veto, resulted fully in agreement with the ICP-MS screening of the same crystal. The natK contamination in the crystal was found to be natK < 4.7 ppb at 90% CL, the lowest potassium level ever achieved in a NaI(Tl) crystal. The low energy spectrum from the full statistics, obtained using a cut-based selection of scintillation events, was analysed and fitted with Montecarlo simulated spectra to build the background model of crystal NaI-33 [4].

In 2021, the PoP setup was modified for crystals characterization without the LS veto. After removing the LS and the vessel, the NaI-33 detector module was placed directly inside the PoP passive PE shielding. To compensate for the missing shielding power of the LS, we added low radioactivity copper (10 cm on the sides and top, 15 cm below) and PE slabs on the sides. The inner volume of the detector module and of the shielding were continuously flushed with high-purity nitrogen gas to avoid moisture and radon. The data acquired between March 17, 2021 and February 25, 2022, for a total exposure of 891 kg×days, were analysed using a multivariate approach to the selection of scintillation events, based on Boosted Decision Trees (BDT) [6]. This allowed us to maximize the signal acceptance at very low energies [4]. The background model of NaI-33 from the PoP-dry data was studied and compared to the one from the PoP run, as shown in section 3.

3. Data analysis and results

We compared in Fig. 1 the NaI-33 energy spectrum below 20 keV acquired with the PoP-dry setup (red points) to the one acquired with the PoP setup (blue points) and which benefits of the anti-coincidence with the liquid scintillator veto. Both the energy spectra are corrected for the acceptance of the event selection: standard 1-dimensional cuts on a set of variables (defined in detail in Ref. [7]) for the PoP and a BDT-based selection for the PoP-dry data. The average count rate in the energy region from 1 to 6 keV is 1.39 ± 0.02 cpd/kg/keV for the PoP-dry. A comparable background level is measured within the PoP setup, i.e. 1.20 ± 0.05 cpd/kg/keV.

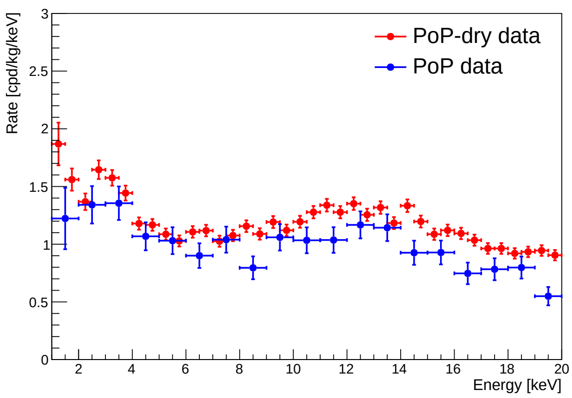

Figure 1: Comparison of NaI-33 low energy spectra (corrected for the acceptance of the event selection) acquired within the PoP-dry (red points) and the PoP setup (blue points). In the latter spectrum, an anti-coincidence cut is applied to reject events with an energy deposition in the liquid scintillator. A wider binning is used for the PoP spectrum, due to the ~10 times lower exposure.

We performed a fit of both energy spectra with a combination of several Montecarlo simulated spectral shapes of background components. The SABRE Monte Carlo simulation code [8] was used to this purpose. We simulated the following background sources in the crystal: ^{40}K, ^{210}Pb, ^{3}H, ^{226}Ra, ^{232}Th, and ^{129}I. We added a contamination from ^{210}Pb in the PTFE reflector wrapping the crystal and a flat component to account for ^{87}Rb in the crystal and other internal and external contributions (such as radioactivity in PMTs), that produce a flat spectrum in the ROI. Finally, we included a contribution from ^{238}U in the quartz window of the PMTs in the fit of PoP-dry data to better reproduce the experimental energy spectrum around 16 keV. The result of the best-fit in the 2-70 keV energy range is shown in Fig. 2 (by extrapolating the spectrum behaviour below 2 keV) for both PoP (χ^2/N_{dof} = 96/88) and PoP-dry ($\chi^2/N_{d.o.f.}$ = 177/127) data. Tab. 1 summarises the activities of the different background components determined from the spectral fits and the corresponding rate in the 1-6 keV ROI. The main features of the background components in NaI-33 are consistent in both the PoP and the PoP-dry spectral analyses. The ^{40}K contribution results to be subdominant, due to the low potassium activity of NaI-33. ^{210}Pb in the PTFE reflector and in the crystal bulk appears to be responsible for most of the background rate. The flat component gives a significant contribution in the ROI in the PoP-dry, as the passive shielding is not yet optimized and environmental gammas may enter the shielding.

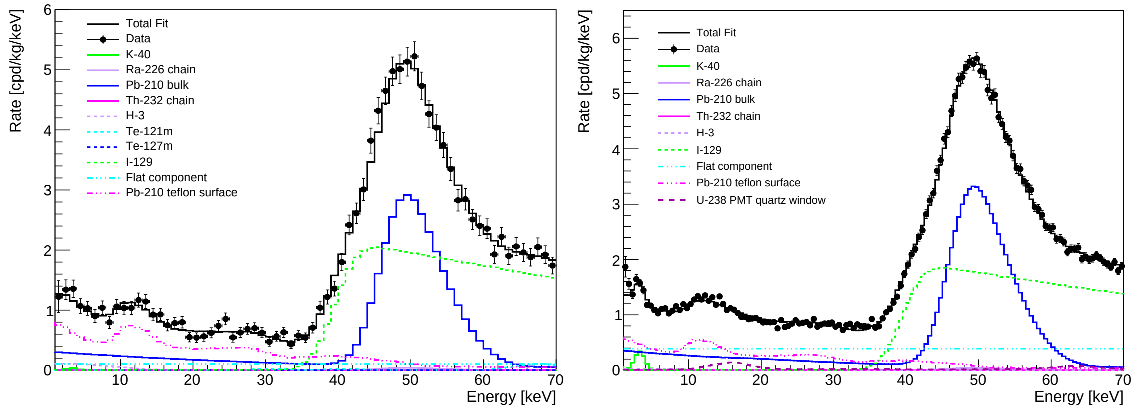

Figure 2: PoP (left) and PoP-dry (right) energy spectrum of the NaI-33 crystal up to 70 keV with a spectral fit. Data are shown after noise rejection and acceptance correction.

	PoP		**PoP-dry**	
Source	**Activity in NaI-33 [mBq/kg]**	**Rate in ROI in NaI-33 [cpd/kg/keV]**	**Activity in NaI-33 [mBq/kg]**	**Rate in ROI in NaI-33 [cpd/kg/keV]**
^{40}K	0.14±0.01	0.02±0.01	0.15±0.02	0.12±0.02
^{210}Pb (bulk)	0.42±0.02	0.28±0.01	0.46±0.01	0.32±0.04
^{226}Ra	0.006±0.001	2*0.004±0.001	0.006±0.001	2*0.004±0.001
^{232}Th	0.002±0.001		0.002±0.001	
^{3}H	0.012±0.007	2*≤0.13	≤0.005	2*≤0.05
^{129}I	1.34±0.04		1.29±0.02	
^{210}Pb (PTFE)	0.32±0.06	0.63±0.09	0.24±0.02	0.46±0.03
^{238}U (PMT quartz window)	-	-	0.09±0.01	0.011±0.002
Other (flat)		0.10±0.05		0.39±0.02
total		1.16±0.10		1.36±0.04

Table 1: Activities and current rate in ROI (1-6 keV) of different background components in NaI-33 from the spectral fit of PoP and PoP-dry data. The activities of ^{210}Pb in the reflector and of ^{238}U in the PMTs quartz window are normalized to the crystal mass for comparison with bulk activities. Upper limits are given as one-sided 90% CL. Rates are conservatively calculated using upper limits.

4. SABRE North upcoming and future activities

The upcoming experimental activities of SABRE North will be focused on demonstrating the findings of our background model by replacing the PTFE reflector on NaI-33 and measuring again the background level with direct counting underground. Furthermore, we plan to demonstrate that the production of ultra high purity crystal at the level of NaI-33 is reproducible. To these aims, a glove box for the handling of NaI(Tl) hygroscopic crystals has been commissioned inside the clean room CR1 in Hall C at LNGS. It will allow us to work under nitrogen atmosphere and avoid radon and humidity while replacing the teflon reflector in the NaI-33 detector module and assembling new detector modules. A new crystals of about 4.5 kg and grown with Astrograde powder, called NaI-37, has been purchased from RMD and is already under storage at LNGS, waiting to be mounted into the copper enclosure (currently undergoing electropolishing at INFN LNL). We have assembled a new refurbished test facility in the SABRE experimental area in Hall B to carry out the crystal characterization activities.

Concerning future perspectives, and especially the possibility to further reducing the background level by getting rid of the ^{210}Pb contamination in the crystal bulk, we plan to exploit the technique of zone refining (ZR), already discussed in [4]. With a ZR equipment developed by PU in collaboration with Mellen Company (USA), a test run was performed that demonstrated a reduction of ^{40}K and ^{87}Rb (from ^{39}K and ^{85}Rb measurements) to negligible levels, and a reduction of ^{208}Pb by at least a factor of 2.5 [9].

5. SABRE South status

The SABRE South project has been seeing huge progresses, with the SUPL laboratory completed and inaugurated in August 2022. Several parts of the SABRE South detector are already available, such as steel vessel, LAB, PMTs, muon detectors, DAQ electronics, slow control, and crystal insertion system. The crystal procurement is on-going, with one low background NaI(Tl) crystal called NaI-35 in testing phase at LNGS. Simulation studies of SABRE South background [10] indicate a background level of about 0.7 cpd/kg/keV, assuming the highest purity crystals and the largest active veto. Further information on the SABRE South setup can be found in Mike Mews's poster [11]. The SABRE North and South detectors have several common core features. They share the same detector module concept, and the software frameworks for simulation, DAQ and data analysis. The exchange of engineering know-how is carried out within official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN. Concerning the shielding design, SABRE North and South detectors have different options: SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS. SABRE South will be the first experiment in SUPL, the LS will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.

6. Conclusion

We described the characterization of the low background NaI(Tl) SABRE crystal NaI-33 into two different setups at LNGS. The PoP-dry, a setup that does not feature the use of a LS veto, shows a minor increase in the background level with respect to the one observed in the PoP with active veto. Our background model finds consistent results between the PoP and PoP-dry spectral features. The dominant background is actually not affected by the veto and can be ascribed to ^{210}Pb in the crystal bulk and in the PTFE reflector. This conclusion opens to a new design of the experimental

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setup for the physics phase of the SABRE North detector. This will be based on an array of crystals with radio-purity similar to NaI-33, wrapped in a specially selected low radioactivity PTFE reflector and it will feature a further improved purely passive shielding.

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