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Status of SABRE North at LNGS and radiopurity of SABRE NaI(Tl) crystals

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SABRE (Sodium-iodide with Active Background REjection) is designed to deploy arrays of ultra-low background NaI(Tl) crystals for a model-independent search for dark matter through the detection of annual modulation signatures. The experiment is dual-site, with detectors located at the Gran Sasso National Laboratory (LNGS) in the Northern Hemisphere and the Stawell Underground Physics Laboratory (SUPL) in the Southern Hemisphere, both supported by a joint R&D program focused on crystal development. Over the past decade, SABRE has conducted extensive research on ultra-radiopure NaI(Tl) crystals, with several crystals grown and tested under active and passive shielding at LNGS.

Based on the results of this R&D, SABRE North is moving towards a full-scale detector design featuring entirely passive shielding. To achieve unprecedented radiopurity levels in NaI(Tl) crystals, SABRE North is employing zone refining to purify NaI powder prior to crystal growth. In this paper, we present the first results from these zone refining activities, along with predictions for the ultimate radiopurity achievable. We also provide an update on the current status of SABRE North's installation at LNGS.

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1. Introduction

The SABRE experiment was designed to conduct a model-independent search for dark matter through the detection of the annual modulation signature, with the goal of achieving unprecedented sensitivity to either confirm or refute the claims made by the DAMA/LIBRA experiment[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[2]) 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 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, especially considering that currently running experiments using NaI(Tl) target such as ANAIS-112[3] and COSINE-100[4] exhibit a signal-to-noise ratio diminished by radioactive backgrounds several times higher than that observed in the DAMA crystals. 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, ^{210}Pb, and ^{3}H, the development of ultra-high purity NaI(Tl) crystals is the path followed by the SABRE collaboration to achieve the 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.

2. Zone refining method and activities

The SABRE strategy aims to enhance the radiopurity of NaI powder through zone refining purification prior to crystal growth[5]. Zone refining is typically used for purifying crystals and involves melting a narrow region of the material, then moving this molten zone along the crystal's axis. The segregation coefficient of an impurity (defined as the ratio of its concentration in the solid phase to the liquid phase) is usually less than one. This means that at the solid-liquid interface, impurities preferentially diffuse into the liquid phase, allowing them to migrate toward the end of the crystal. By repeating this process, the impurity concentration can be reduced to the desired levels. After purification, the final crystal is produced from the section of the ingot near the starting point of the molten zone, while the end portion, where the impurities have accumulated, is discarded. This technique can also be applied directly to an ampoule containing pre-melted NaI powder, producing a purified ingot from which the final NaI(Tl) crystal is grown. The SABRE Princeton group, in collaboration with Mellen (a manufacturer of high-temperature furnaces and refractory materials based in Concord, New Hampshire, USA), designed a zone refining system equipped with three furnaces. This equipment, shown in Figure 1(a), is large enough to effectively produce kilogram-sized crystals. The three annular furnaces move simultaneously on a motorized track along the ingot, performing multiple zone refining steps. A novel feature of the SABRE zone refiner is its continuous operation mode. In conventional systems, the furnaces (if more than one) must complete their path before being returned to the starting position on the same track to repeat the process. In the SABRE design, however, the furnaces can open like a clamp and return to the starting position on a lower-level track, separate from the operational tube. The entire process is computer-automated, with different speeds programmed for the upper and lower-level movements.

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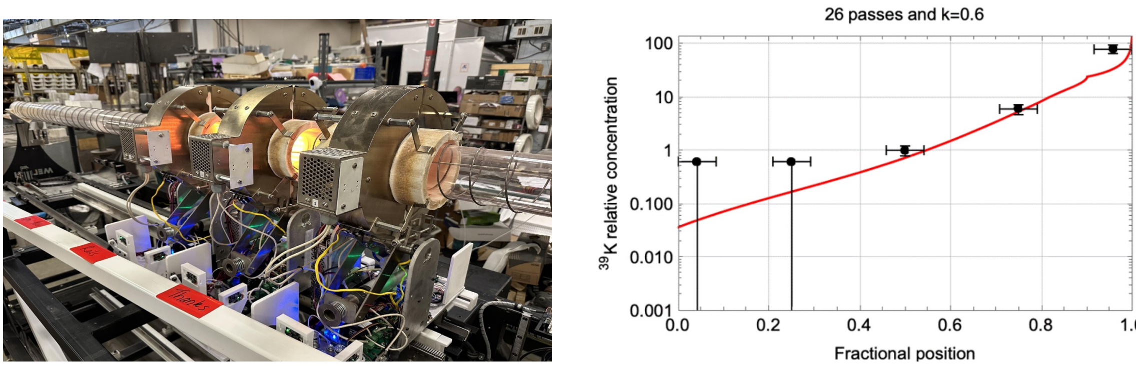
The zone refining process commenced at MELLEN in late September 2023, in collaboration with



(a) **(b)**

Figure 1: (a) Zone refining equipment in operation at Mellen. (b) Comparison of zone refining data for Potassium in Run1 against the model.

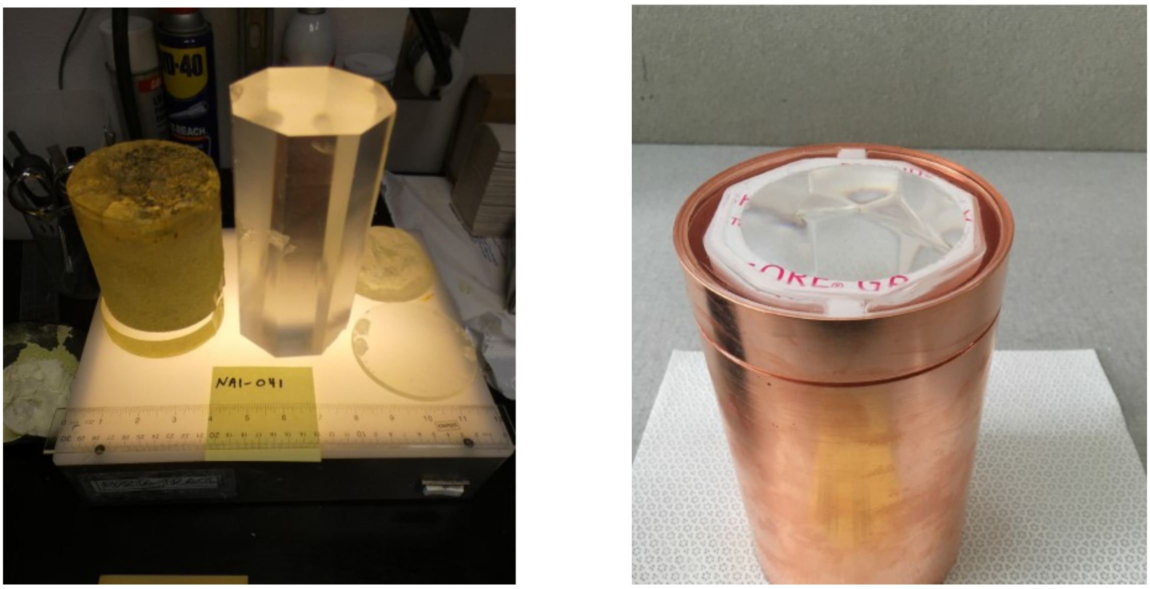
RMD (Radiation Monitoring Devices, MA, USA), which supplies the ampoules containing the NaI powder. The zone refiner is equipped with a quartz tube that allows pre-heating up to 200°C. Before the actual zone refining begins, a consolidation run is performed. This process melts the powder inside the ampoule, forming a solid ingot. Once the ingot is formed, the ampoule is transferred into the preheating tube to initiate the zone refining process. The purification efficiency during zone refining is determined by the segregation factor, which is the ratio of impurity concentration between the solid and liquid phases. For potassium, this factor is expected to range between 0.5 and 0.7. This expectation is supported by our analysis of several samples taken from the extreme ends of the crystal ingot after production, that allow to evaluate a model of the expected concentration for different numbers of passes.

Four purification runs have been carried out to test the powder under different operating conditions. These variations included adjustments in ampoule treatment, the number of zone refining passes, and furnace speed, all aimed at identifying the optimal configuration for the project. For each run, five samples were collected from the ingot and analysed via ICP-MS (Inductively Coupled Plasma Mass Spectrometry). In Figure 1(b) we compare our expected concentration model (red curve) to the data from Run 1, using a segregation factor of 0.6 for potassium. Although the comparison is not based on a formal fit, it illustrates that below the fractional position of 0.75, the average purification efficiency is around 87%. For instance, an initial potassium contamination of 10 ppb is reduced to approximately 1 ppb.

3. Crystal production for validation phase

Crystals for SABRE North will be produced by RMD, using Astro Grade powder (produced by Sigma Aldrich now Merck, Germany) that has been zone refined by MELLEN. As of today, five SABRE NaI(Tl) crystals have been produced, all grown by RMD using ultra-pure NaI powder and the Vertical Bridgman method. The first two crystals, NaI-31 and NaI-33, were extensively tested and characterized, as documented in [6]. Two more crystals were acquired recently and have also been characterized to assess the reproducibility of the crystal production process. It was found that, within a factor of two, RMD can consistently reproduce the crystal radiopurity, even accounting for differences in the powder used. Considering the zone refining purification process mentioned earlier, we expect these differences to diminish, resulting in a higher overall radiopurity. Therefore, the reproducibility of the growth process is considered satisfactory.

The most recently produced crystal, NaI-41, was grown using chunks from a previously undoped NaI crystal, itself grown from Astro Grade powder sourced from two different lots. In cases where zone refining is used as the purification method, the crystal growth ampule is loaded with chunks of the purified ingot rather than powder. The successful growth of NaI-41 was not guaranteed in advance. However, NaI-41 has proven to be a very good crystal in terms of both optical and scintillation characteristics, providing a crucial test for the future production of crystals grown entirely from zone refined powder. We show in Figure 2 a few pictures of NaI-41 after growth and encapsulation. The crystal has been underground at LNGS since December 2023.

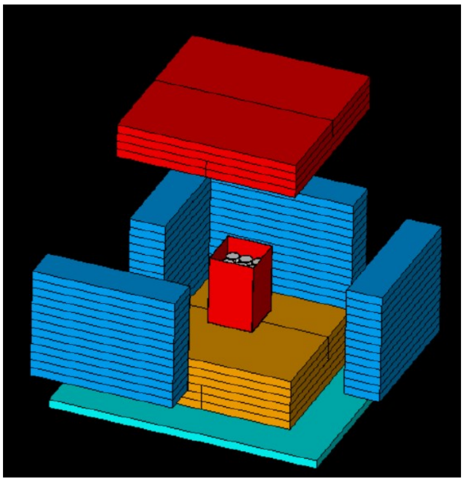


(a) **(b)**

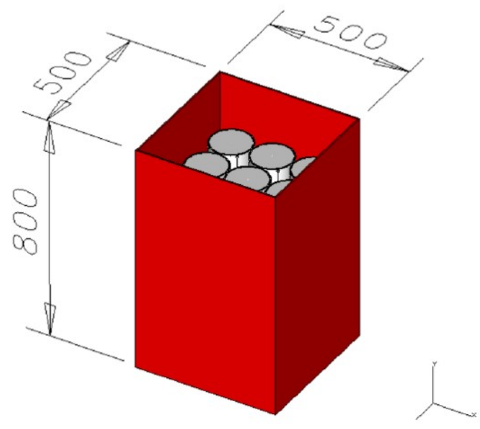
Figure 2: (a)NaI-41 crystal after growth, and (b) NaI-41 encapsulated and ready for shipment.

4. Towards the full scale experiment

In 2023, a new final location for SABRE North was discussed and identified in agreement with the LNGS (Laboratori Nazionali del Gran Sasso) management. The proposed setup consists of an array of nine detector modules arranged in a 3x3 matrix, housed within a purely passive shielding structure. The shielding is designed to reduce the external background, primarily environmental gamma radiation, within the region of interest (ROI) to a level of 10^{-3}cpd/kg/keV. The shielding has a layered structure, consisting of 25 cm of copper and at least 50 cm of polyethylene. The entire shielding structure is supported by a 10 cm thick copper base. A preliminary design is shown in Figure 3(a). The systems associated with the NaI(Tl) detector modules are among the most complex components of the experiment. This complexity arises from the need to protect the NaI(Tl) crystals from moisture, laboratory air, radon, and other contaminants during handling, assembly, and deployment. Each detector module is the core of SABRE and consists of a high-purity NaI(Tl) crystal, weighing approximately 5 kg, wrapped in a PTFE reflector. The crystal is coupled to two 3-inch Hamamatsu R11065-20 photomultiplier tubes (PMTs) and mounted inside a low-radioactivity copper enclosure. The main body of the enclosure is a copper tube, open on one side, with a total length of 63.4 cm. The internal structure is made up of copper (bars and rings) and Delrin (rings) components, ensuring proper coupling of the PMTs to the crystal and a stable positioning of all elements within the enclosure. The copper cap is equipped with feedthroughs for high voltage, signal output, and nitrogen flushing. Assembly of the detector module will take place in a dedicated glove box under a nitrogen atmosphere, due to the highly hygroscopic nature of sodium iodide. To further mitigate the risk of moisture contamination, all parts will undergo thermal treatment prior to assembly. The inner volume of the enclosure will be continuously flushed with high-purity nitrogen to prevent moisture buildup. The entire 3x3 crystal array will be housed in a sealed copper box with 5 mm thick walls and external dimensions of 50 x 50 x 80 cm^3, which will also be flushed with nitrogen (see Figure 3(b)). This enclosure forms a critical barrier against radon infiltration.



(a)



(b)

Figure 3: (a) Rendering of the PE shielding for the SABRE experiment (exploded view). The volume between the PE shielding and the inner copper box is filled with copper (here not shown). (b) The SABRE crystal array inside the 5 mm thick copper box, with external dimensions (in mm)

5. Conclusions

The goal of SABRE is to search for an annual modulation signal using two NaI(Tl) detectors, one in the Northern Hemisphere and one in the Southern Hemisphere. With this dual-hemisphere approach, SABRE aims to confirm or exclude the presence of annual modulation within 3 to 5 years of operation. This would provide crucial evidence either supporting or refuting the DAMA/LIBRA experiment's long-standing claim of dark matter detection. The Technical Design Report (TDR) for the physics phase detector of SABRE North presented in June 2024, is now approved, marking a major milestone toward the operational phase. The experiment will utilize a 3x3 matrix of high-purity NaI(Tl) crystals, each weighing approximately 5 kg, which will be housed within a fully passive shielding system comprising 25 cm of copper and 50 cm of polyethylene. This design provides sufficient shielding power, ensuring negligible contribution to the total background, a critical factor for the low-background detection required by SABRE. A key aspect of SABRE's development is the use of zone refined Astro Grade NaI powder, which has been rigorously tested across four runs. These tests demonstrate a reduction in several key background sources, providing confidence in the approach to crystal production.

With the planned installation and testing timeline, the SABRE North experiment is poised to make significant contributions to the ongoing search for dark matter, providing results with unprecedented sensitivity and confidence in background reduction.

References

[1] R. Bernabei, et al., The DAMA project: Achievements, implications and perspectives, *Prog. Part. Nucl. Phys.* **114** (2020) 103810.

[2] L. Milligan, et al.,The SABRE South Experiment at the Stawell Underground Physics Laboratory, *in these proceedings*.

[3] J. Amaré, et al., Annual modulation results from three-year exposure of ANAIS-112, *Phys. Rev. D* **103** (2021) 2021102005.

[4] G. Adhikari, et al., Three-year annual modulation search with COSINE-100, *Phys. Rev. D* **106** (2022) 052005.

[5] B. Suerfu, et al., Zone Refining of Ultrahigh-Purity Sodium Iodide for Low-Background Detectors, *Phys. Rev. Applied* **16** (2021) 014060.

[6] F. Calaprice et al., Performance of the SABRE detector module in a purely passive shielding, *Eur. Phys. J. C82 (2022) 1158.*