The SABRE Proof of Principle

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Abstract. SABRE is a dark matter direct detection experiment based on NaI(Tl) scintillating crystals. The primary goal of the experiment is to test the dark matter interpretation of the DAMA/LIBRA annual modulation signal. To reach its purpose, SABRE will operate an array of ultra-low background NaI(Tl) crystals within an active veto, based on liquid scintillator. Finally two twin detectors will be used, one in the northern hemisphere at Laboratori Nazionali del Gran Sasso, Italy (LNGS) and the other, first of its kind, in the southern hemisphere, in the Stawell Underground Physic Laboratory (SUPL). The collaboration has successfully developed a NaI(Tl) crystal with the impressive potassium content of about 4 ppb, according to the mass spectroscopy measurements. A value that, if confirmed, would be about 3 times lower than the DAMA/LIBRA crystals one. The first phase of the SABRE experiment, called SABRE Proof of Principle (PoP), aims to prove the achieved radiopurity by direct measurement of crystals at LNGS. This work reports the status of the PoP setup and the recent progresses on the development of low radioactivity NaI(Tl) crystals.

1. Introduction

Weakly Interacting Massive Particles (WIMP) are considered one of the most promising candidate for Dark Matter and their direct detection can be investigated in underground laboratories. Indeed, according to the expectation of a Dark Matter halo surrounding the galaxy, the presence of WIMPs could be detected by measuring the recoil energy of nuclei eventually scattered off in a particle detector. In this scenario the expected deposited energy is below few tens of keV. Nevertheless, because of the combined motion of Earth and Sun, the event rate for that interactions should modulate over the year, providing a clear signature [1]. This effect, called annual modulation, has been registered with tallium-doped sodium iodide, or simply NaI(Tl), scintillating crystals by the DAMA/LIBRA experiment [2] at Laboratori Nazionali del Gran Sasso (LNGS), Italy. Over a period of more than 15 years a modulating signal has been observed with a statistical significance if 12.9 σ. On the other hand this impressive result appears in tension with other experiments based on different target materials, e.g. the XENON1T experiment [3]. The different target materials make the comparison model dependent so a more direct measurement, with NaI(Tl crystals, is essential to test the DAMA result and clarify the origin of the modulation.

2. SABRE project

The SABRE (Sodium Iodide with Active Background REjection) aims to test DAMA/LIBRA results by means of the same technique: NaI(Tl) scintillating crystals coupled to photomultipliers tubes. In order to enhance the sensitivity to the annual modulation signal, some main improvements will be introduced with respect to the DAMA design: i) first the background rate will be reduced as much as possible using ultra-radiopure custom-made crystals [4] and operating them into a liquid scintillator veto. Indeed an active veto also offers the capability of to tag particular isotopes such as ^{40}K, a dangerous crystal contaminant since it emits 3 keV Auger electrons. Our goal is to get a background lower than the DAMA one (1 cpd/kg/keV). ii) A good light collection will allow to use a low energy threshold, possibly lower than 2 keV. The importance of the threshold comes from the shape of the recoil energy spectrum: the lower the energy the higher is the expected WIMP-induced rate. Such result can be achieved by using high quantum efficiency photomultiplier tubes (PMT) directly coupled to the crystals, so that the light loss is reduced. iii) Finally the possibility to run two similar detectors in both the northern and the southern hemispheres will help to disentangle seasonal effects from halo-related effects. In addition to the SABRE-North detector at LNGS a second detector called SABRE-South will operate in a new laboratory, the Stawell Underground Physics Laboratory, currently under construction in Australia.

The SABRE project is divided in two phases. The first, called Proof of Principle (PoP), aims to validate the veto effectiveness and to provide a direct measurement of the background achieved in the crystals produced by the collaboration. In this phase one or few crystals (about 5 kg each) will be measured at the same time. Then two crystal arrays of about 50 kg each, whose actual size will depend on the crystal radiopurity, will be used for the full-scale experiments.

3. SABRE Proof of Principle setup

The core of PoP setup at LNGS is essentially composed by a detector module, the active veto and the passive shielding. The detector module is composed by a sealed copper cylinder hosting a single NaI(Tl) crystal, 4" in diameter, and two Hamamatsu R11065-20 3" PMTs. The internal structure includes the rods, the crystal holders and the PMT holders, and is designed to sustain crystal and PMTs while ensuring a stable optical contact between them, see fig 1.

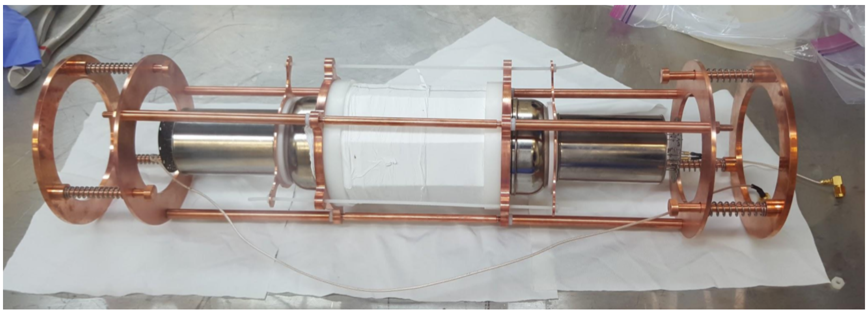

Figure 1. Content of the SABRE PoP detector module. The NaI(Tl) crystal is wrapped in PTFE tape to enance light reflection and is kept in position by two holders while the two PMTs are gently pushed against it.

The cylindrical shell, the end-caps and the internal parts, all in copper, are made by Alca Technology company, while some parts of the holders are made out of high-purity PTFE. Given the high hygroscopicity of NaI and the radiopurity requirements, all these parts must be thermally treated before the assembly. Electrical feedthroughs and connectors for nitrogen purging are located on the top end-cap. Indeed the module will operate in vertical position inside the veto vessel: a 1.3 m (diameter) × 1.5 m (length) cylindrical vessel filled with about two tons of liquid scintillator and instrumented with ten Hamamatsu R5912-100 8" PMTs. The veto vessel and all the external structures are visible in fig 2. The liquid scintillator will be pseudocumene, distilled by the Borexino facility, doped with 3 g/l of PPO (2,5)-diphenyloxazole acting as wavelength shifter. The inner surface of the stainless steel vessel is coated with Ethylene tetrafluoroethylene (ETFE), to prevent scintillator degradation due to direct contact with the stainless steel, and covered with Lumirror $^{\mathrm{TM}}$ foils to improve light reflection. The detector module can be inserted into the veto vessel via a 20 cm diameter top flange, connected to a 2 mm thick copper tube designed to host the module while preventing the contact between the module and the pseudocumene. This approach offers the capability to change the detector module, to test different crystals, without to expose pseudocumene to air. The detector and the fluid handling system includes also a slow control system providing a continuous monitoring of all the relevant parameters such as temperature, pressure, and radon emanation, needed for both security reasons and physics analysis.

To further shield the setup from external radiation, the vessel is surrounded by several layers of passive material. From the inside a shield of polyethylene delimits a tight volume that will be flushed with nitrogen to remove radon from the detector surroundings and to create an inert atmosphere. The polyethylene shield is 40 cm on the sides, with the exception of the door (not shown in the figure) which is 65 cm tick, and the top and bottom plates that are 10 cm each. The top polyethylene plate supports a 2 cm steel plate at the top where the crystal insertion system (CIS) can be mounted when needed. The CIS, visible in figure, is essentially composed by a structure supporting a winch with a precise alignment system, allowing to slowly lower the detector module inside the veto vessel. A set of water tanks forms a layer of 80 cm on the sides (white tanks) and of 90 cm on the top (blue tanks). Finally the setup is placed on a layer of 15 cm of lead.

4. SABRE status

The Sabre PoP setup construction is completed, the veto vessel can be filled with the liquid scintillator and all the subsystems such as the fluid handling, the acquisition and the slow control are ready for operation. While waiting the authorization to operate the PoP setup, we started the characterization of a SABRE crystal by means of a small shielding in the experimental hall B of LNGS. The shielding is totally passive and composed by a 5-10 cm (depending on the direction) copper layer surrounded by a 17.5 cm lead layer. SABRE crystals are grown with the commercial partner Radiation Monitoring Devices company in Boston using the vertical Bridgman method. Astro Grade NaI powder is used because of its low contamination levels of K (9 ppb), Rb (<0.1 ppb), U (<1 ppt) and Th (<1 ppt). In middle 2019, an octagonal crystal, named NaI-33, has been prepared to be measured at LNGS. Inductively coupled plasma mass spectroscopy (ICP-MS) measurements performed at Princeton University reported a K content of 4 ppb; it is a very promising value being it 4 times smaller than the one reported by DAMA/LIBRA (13 ppb)[5] and nine times lower than the one reported by ANAIS-112 (32 ppb)[6] and COSINE100 (42 ppb)[7]. The crystal module has been assembled in glove box and shipped to Italy by boat to reduce cosmogenic activation. NaI-33 crystal measurements started in middle August 2019. We first measured light yield and energy resolution by placing an ^{241}Am source just outside the detector module. We measured a total light yield of about 11 photoelectrons/keV and an energy resolution of 12.3% at 59.5 keV. Background characterization

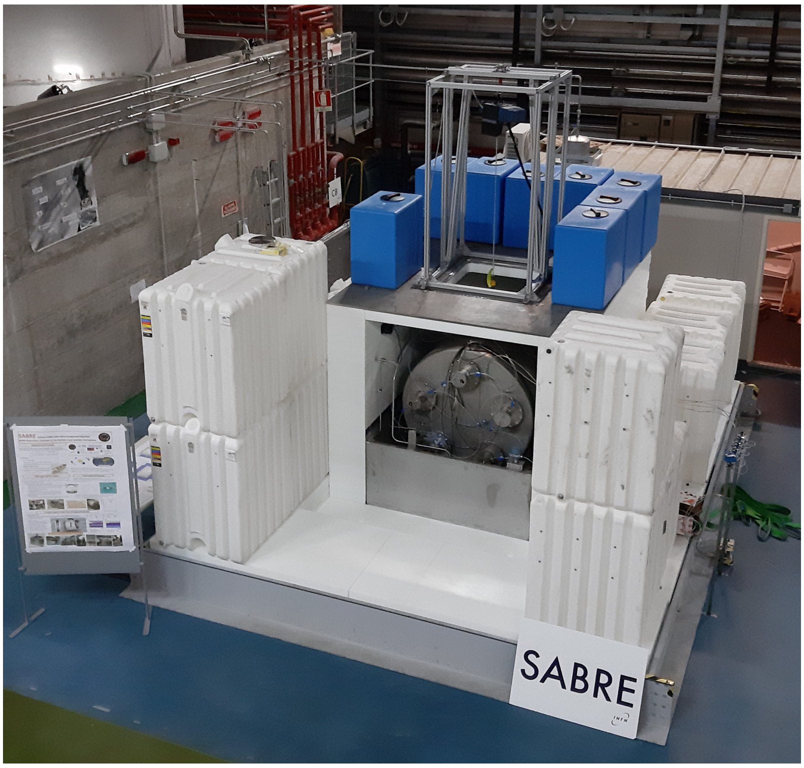

Figure 2. The SABRE Proof of Principle setup in hall C of LNGS. A side of the cylindrical veto vessel with five PMT housings is visible in the centre of the polyethylene shield, which is surrounded by water tanks. The removable structure mounted on top of the shielding is the crystal insertion system.

is currently limited by the presence of cosmogenic isotopes so we first focused on alpha decays that can be easily identified by the charge-weighted mean-time. Alpha activity turned out to be (0.48 ± 0.01) mBq/kg but we also found indications that most of this rate is due to ^{210}Po decays from a ^{210}Pb contamination out of equilibrium. The current analysis activity is focused on the development of noise rejection algorithms and on energy threshold reduction with the intent to better understand the low energy region of the spectrum and to produce a first background model capable to assess crystal contaminations.

5. Conclusions

The SABER experiment goal is a direct test of the annual modulation signature detected by the DAMA/LIBRA experiment at LNGS, with improved sensitivity and lowered background. We concluded the construction of the Proof of Principle apparatus, designed to validate the veto rejection power and to measure background levels in the NaI(Tl) crystals produced by the collaboration. While waiting the authorization to operate the PoP setup, we started the characterization of NaI-33 crystal whose K contamination level, measured by ICP-MS, could be the lowest ever achieved in such kind of detectors.

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