PROCEEDINGS OF SCIENCE

# SABRE
# NaI(Tl) Dark Matter Investigation at low Radioactivity

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The interaction rate of hypothesised Dark Matter particles in an Earth bound detector is expected to undergo an annual modulation due to the planet's orbital motion. The DAMA experiment has observed such a modulation with high significance in an array of scintillating NaI(Tl) crystals, however this results remains today unconfirmed. SABRE aims to perform a higher sensitivity measurement with NaI(Tl) crystals able to verify the claim in a model independent way, but also to investigate the nature of Dark Matter interaction and the characteristics of the Dark Matter halo. This will be possible thanks to a lower background in the signal region and a lower energy threshold: we are developing high purity NaI(Tl) crystals, recently matching the purity of DAMA; moreover SABRE will enforce a $4\pi$ active background rejection with liquid scintillator and photomultiplier tubes with a lower background and a higher quantum efficiency. Our future design includes a pair of twin detectors at LNGS (Laboratori Nazionali del Gran Sasso, Italy) and SUPL (Stawell Underground Physics Laboratory, Australia). The combined analysis of data sets from the two hemispheres will allow to identify any terrestrial contribution to the modulating signal. We present here the progresses made on crystal development, the status of the Proof-of-Principle detector currently being installed at LNGS and the potentiality of the future detectors.

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*Speaker.

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PoS(NOW2016)086

**Introduction.** Several compelling evidences today point to the existence of Dark Matter (DM) in the form of a new particle beyond the Standard Model [1]. Such hypothesised particle would be neutral, stable on a cosmological scale and (very) weakly interacting. Galaxies like ours are supposed to be immersed in a DM halo. Due to the motion of the solar system within the halo, an Earth-bound detector would experience a DM "wind". Moreover the interaction rate would be slightly modulated due to the orbital motion of the Earth. Such a modulation would be a unique and model independent signature of DM interaction [2]. The DAMA experiment at Laboratori Nazionali del Gran Sasso (LNGS) has observed a modulation of the scintillation signal in NaI(Tl) crystals. The DAMA/NaI and the subsequent DAMA/LIBRA detectors, with a mass of 100kg and 250kg respectively, have collected data for a total of 13 annual cycles. The statistical significance of the modulation is beyond question (9.3$\sigma$) and it could be interpreted as due to Weakly Interactive Massive Particles (WIMPs) of $\sim$10 GeV ($\sim$80 GeV) elastically scattering off Sodium (Iodine) nuclei with a WIMP-nucleon spin-independent cross-section of $\sim 10^{-40}$cm$^2$ ($\sim 10^{-41}$cm$^2$) [3]. Experiments using different targets and techniques fail to observe signals due to WIMPs with the same mass and cross-section [4]. However the comparison of these results implies several assumptions (e.g. DM velocity distribution, nature of DM candidate and interaction). The only model independent verification of this result can come from a new experiment based on NaI(Tl) scintillators. SABRE (Sodium iodide with Active Background REjection) aims to clarify the controversy with a detector able to go beyond the sensitivity and below the energy threshold of DAMA. Should the modulation be actually due to DM interaction, SABRE would be capable of a next level of investigation: explore the nature of interaction, the characteristics of the halo and the eventual focusing gravitational effect of the Sun [5]. With these goals in mind, SABRE is designed on four building pillars: the use of high purity crystals (1), the active rejection of background with liquid scintillator (2), the use of new Photomultiplier Tubes (PMTs) with low background and high quantum efficiency (3), the use of two twin detectors located on opposite hemispheres (4).

**Backgrounds and crystal development.** DAMA observes a modulation between 2 keV and 6 keV in the energy scale of electron recoils. The most dangerous source of background in this energy region is due to $^{nat}$K impurities in the crystals. The isotope $^{40}$K (0.012% of $^{nat}$K ) decays to $^{40}$Ar via EC with $\sim$10% branching ratio. The energy of the K-shell of $^{40}$Ar is $\sim$3 keV, very similar to the energy at which maximum amplitude of modulation is observed. The average $^{nat}$K content in DAMA crystals is $\sim$13 ppb. Reducing the $^{nat}$K content in the crystals at or below this level is therefore mandatory in order to improve the sensitivity of a new NaI(Tl) detector. The SABRE collaboration together with industrial partners has developed an ultra-pure NaI powder now avail-

| Element | DAMA powder [ppb] | DAMA crystals [ppb] | Astro-Grade [ppb] | SABRE crystal [ppb] |
|---|---|---|---|---|
| K | 100 | $\sim$13 | 9 | 9 |
| Rb | n.a. | <0.35 | <0.2 | <0.1 |
| U | $\sim$0.02 | 0.5-7.5$\times 10^{-3}$ | $<10^{-3}$ | $<10^{-3}$ |
| Th | $\sim$0.02 | 0.7-10$\times 10^{-3}$ | $<10^{-3}$ | $<10^{-3}$ |

**Table 1:** Contaminations in Astro-Grade NaI powder and in SABRE 2-kg test crystal compared to DAMA.



PoS(NOW2016)086

able under the commercial name Astro-Grade. The latest production batch shows a contamination of $^{39}$K of $\sim$9 ppb. Other contaminants are also pretty low: 0.2 ppb of Rb, $<$1ppt for U and Th, all comparable or better then DAMA [6]. Measuring such low concentration of impurities has required the development of ad-hoc procedures improving the sensitivity of ICP-MS, ICP-OES and AMS in several laboratories (Seastar, PNNL, LNGS, ANU, Spectro/Ametek). Redundant and consistent measurements ensure the reliability of our figures. Out of this powder we have first grown a 2-kg crystal (3.5" diameter) with the collaboration of the company RMD (Radiation Monitoring Devices, Boston, USA). The growth process in principle can improve the purity by segregating impurities in the periphery of the crystal which is later removed. However extreme care must be placed in the handling of materials, in the growth procedure, in the cut and in the surface treatment in order to prevent recontamination. Our test crystal shows a $^{39}$K concentration of $\sim$9 ppb, similar concentration as the starting powder and below the average value of DAMA. This is a breakthrough in crystal development, after several years of world wide efforts during which the background level of DAMA crystals has remained unmatched. The concentration of $^{87}$Rb is below our detection limit of 0.1 ppb (DAMA upper limit: 0.35 ppb). We are currently growing the first full size crystal ($>$5 kg) to be tested in 2017 in the Proof-of-Principle detector described below. SABRE also reduces several backgrounds by immersing the crystals in organic liquid scintillator acting as a veto. In particular, the $^{40}$K decays to $^{40}$Ar is accompanied by a 1.46 MeV de-excitation gamma. Thanks to a $4\pi$ gamma catching capability the contribution of $^{40}$K background can be reduced by $\sim$80% according to our Monte Carlo (MC) simulations. A summary of contamination levels in the NaI powder and in the test crystal is reported in Tab. 1 and compared to DAMA contaminations.

**Energy threshold and PMTs.** The analysis threshold of DAMA is set at 2 keV, past low energy background and noise events from the PMTs. It is of fundamental importance to uncover the spectral region below this threshold in order to improve the signal collection. Moreover scattering of WIMPs off Sodium as opposed to Iodine nuclei feature modulation amplitudes which differ significantly only below 2 keV. One of the key elements for a low energy threshold are the PMTs. SABRE will start with the R11065-20 model, a 3" device developed by Hamamatsu for low background experiments such as DarkSide [7]. These devices, with a radioactive contamination as low as 5.5 mBq/PMT [8], will be coupled directly to the crystal surface without the need of a light guide, resulting in an improved light collection efficiency. Moreover we plan to operate the PMTs below the nominal gain in order to reduce the emission of after-glow light which can travel back to the crystal and be seen by the opposite PMT resulting in coincident signals that would match the trigger condition. We compensate for the reduced gain with low noise custom preamplifiers mounted on the back of the PMTs. We are also working with Hamamatsu in order to improve the devices for our needs in two ways. First we aim at replacing the ceramic stem with individual ceramic pin feedthroughs which would improve the PMT stability, lower the light emission and further reduce the radioactive background. Second we aim at replacing the photocathode, designed for low temperature operation, with a Super Bialkali photocathode for a slightly higher quantum efficiency and much lower dark noise at room temperature.

**Proof-of-Principle detector.** During 2017 we will proceed to the Proof-of-Principle (PoP) phase of the experiment at LNGS for a complete characterization of the backgrounds past the sensitivity of mass spectroscopy and a validation of the veto power. We will operate the first full size (>5 kg) crystal wrapped in reflective material and coupled to PMTs within a low radioactivity cop-



PoS(NOW2016)086

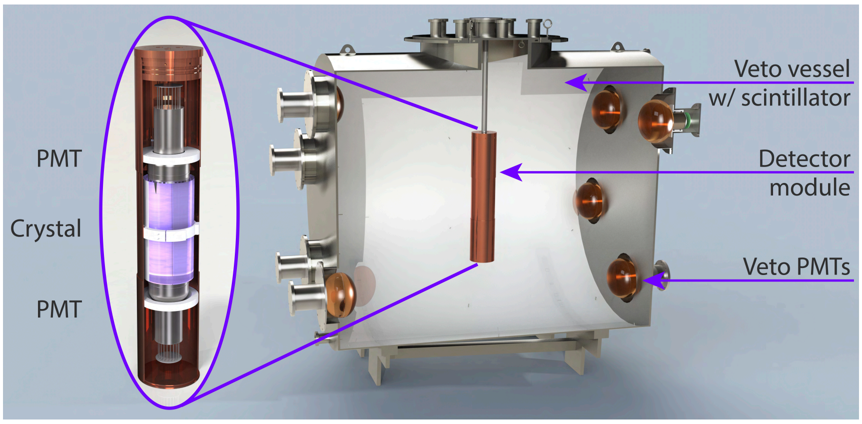


**Figure 1:** 3D drawing of the Proof-of-Principle detector.

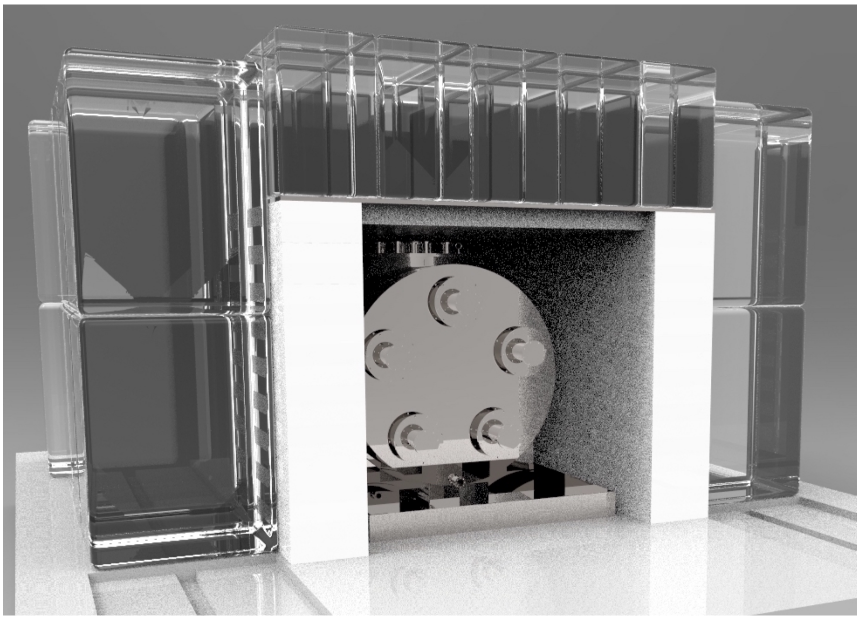

**Figure 2:** The vessel within the shielding made of a lead basement, polyethylene walls (white) and water tanks (gray).

per enclosure. The latter will be immersed in liquid scintillator: ∼2 tons of pseudocumene doped with PPO as wavelength shifter contained in a cylindrical stainless steel tank (1.5m diameter, 1.4m length). The tank is equipped with ten 8" PMTs (Hamamatsu R5192). The light yield expected form MC simulations is ∼0.22 pe/keV thanks to a reflective Lumirror layer on the inner surface of the tank. Passive shielding around the vessel includes a lead basement, polyethylene walls and ∼1 m water tanks. 3D drawings of the PoP detector and its shielding are shown in Figs. 1 and 2.

**Expected spectrum and sensitivity.** We have simulated the detector geometry including the scintillator veto and the shielding. We have assumed that the crystal impurities are those measured in the 2-kg test crystal. The simulated energy spectrum of SABRE past the application of the veto



PoS(NOW2016)086

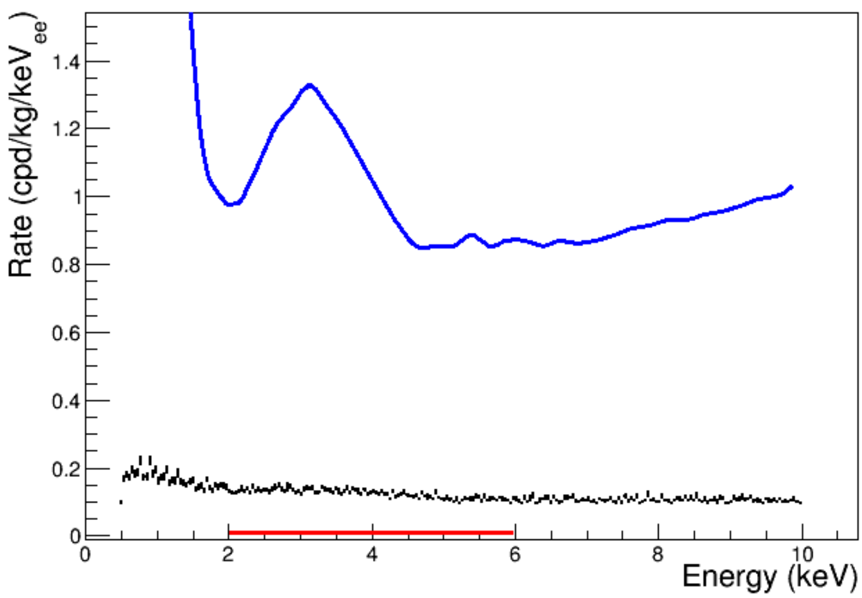


**Figure 3:** The simulated background spectrum (black) after the application of the veto compared with DAMA (blue). The energy region and the amplitude of the DAMA modulation are shown with a red bar.

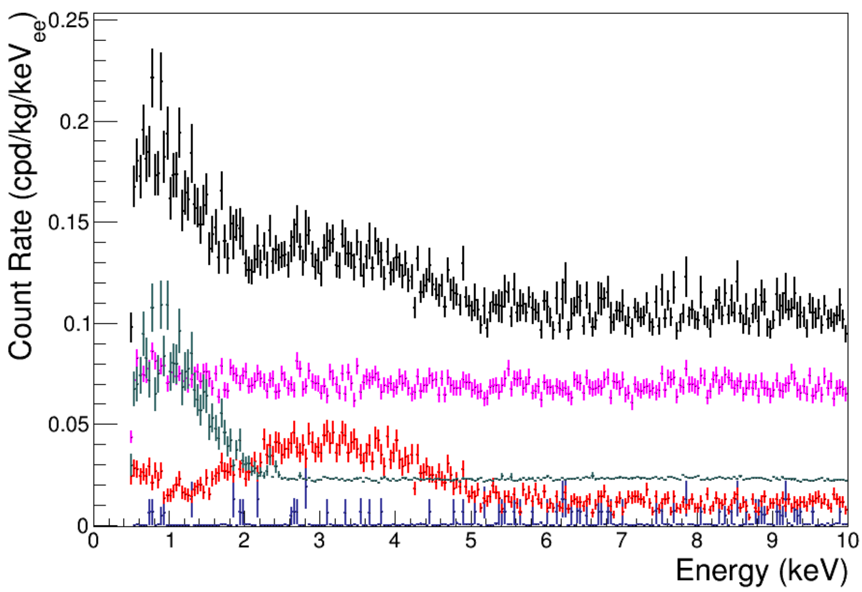


**Figure 4:** Expected background broken into its main contributions. Crystal backgrounds: $^{40}$K (red), $^{87}$Rb upper limit (purple), U and Th (green). The dark blue line includes all non-crystal contributions (PMTs, Enclosure, Vessel, Rocks, etc.).

PoS(NOW2016)086

is shown in Fig. 3 and compared to DAMA. The contributions from the main contaminants in the active volume can be seen in Fig. 4. The total background in the region of interest amounts to 0.13 cpd/kg/keV and is dominated by $^{87}$Rb which has been assumed equal to the mass spectrometry detection limit. The actual background could therefore be significantly lower. Determining other potential backgrounds such as $^{3}$H and $^{210}$Pb, which are below the detection limit of mass spectrometry, is among the main goals of the PoP run. Backgrounds external to the crystals are also included in the simulation. The main sources of external background that have been considered are the PMTs, the copper enclosure, the vessel and the rocks surrounding the laboratory. The contribution from external backgrounds results negligible.

We have studied the sensitivity of a 50-kg detector running for three years with these backgrounds. Introducing a modulating signal with the amplitude observed by DAMA (see Fig. 5) we obtain 4 $\sigma$ power to confirm the observation. In absence of such signal we obtain 6 $\sigma$ power to refute DAMA.

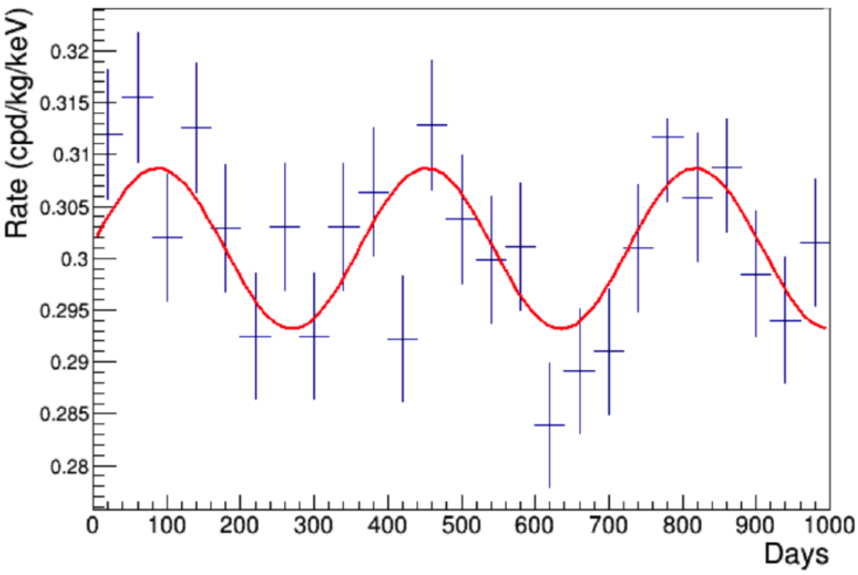


**Figure 5:** Simulated signal's modulation as it would appear in a 50-kg detector for a 3-y data taking.

**Outlook.** The SABRE experiment will proceed with the construction of two twin detectors, whose exact mass will depend on the final backgrounds measured during the PoP phase. One will be located at LNGS while the second one will be located at SUPL (Stawell Underground Physics Laboratory), the new laboratory currently under construction at the Stawell Gold Mine (Victoria, Australia). SUPL [9], whose completion is scheduled by end 2017, will be the first laboratory is the southern hemisphere. The rock coverage of ~3000 m w.e., the access by road and the measured background conditions are similar to LNGS, once radon-free air is supplied from the surface. The availability of data from two very similar detectors located on opposite hemispheres will be a major asset for SABRE as any season-related contribution to the observed modulation would have opposite phase in the two detectors, unlike a DM signal.

**Conclusion.** SABRE aims at a model independent test of the DAMA result but at the same time it will be a better sensitivity NaI(Tl) experiment thanks to the higher purity crystals, the use of



PoS(NOW2016)086

an active background veto, and an improved light collection efficiency. We have recently obtained a breakthrough in crystal development with a 2-kg crystal radio-purer then DAMA crystals and we are currently producing a full size one. In 2017 we will fully characterize the crystal backgrounds in our Proof-of-Principle detector at LNGS. We will then proceed to the installation of two twin detectors in laboratories on opposite hemispheres, LNGS and SUPL, for a unique investigation into DM modulation.

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PoS(NOW2016)086