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Physics Procedia 61 (2015) 169 – 178
Physics Procedia

SABRE: A new NaI(Tl) dark matter direct detection experiment

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Abstract

SABRE (Sodium-iodide with Active Background REjection) is a new NaI(Tl) experiment designed to test the DAMA/LIBRA claim for a positive WIMP-dark matter annual modulation signal. SABRE will consist of highly pure NaI(Tl) crystals in an active liquid scintillator veto that will be placed deep underground. The scintillator vessel will provide a veto against external backgrounds and those arising from detector components, especially the 3 keV signature from the decay of ^{40}K in the crystal. Through the use of crystal purification techniques and the veto, we aim for a ^{40}K background significantly lower than that of the DAMA/LIBRA experiment. We present our work developing low-background NaI(Tl) crystals using a highly pure NaI powder and the development of the veto.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: dark matter, WIMP, NaI(Tl), DAMA-LIBRA,

1. Introduction

There now exists a wealth of empirical evidence showing that a gravitationally-interacting dark matter makes up the majority of the mass in our Universe. One potential candidate for this dark matter is a Weakly Interacting Massive Particle (WIMP). The WIMP-nucleus interaction rate is expected to modulate yearly due to the Earth's rotation around the Sun. For over a decade, the DAMA experiment (DAMA-NaI and DAMA-LIBRA), situated at Gran Sasso National Laboratory (LNGS), has been observing a low energy (2-6 keV$_{ee}$) rate modulation in an array of high purity NaI(Tl) crystal detectors [1], as shown in Fig. 1 (top). This modulation occurs with a phase and period consistent with predicted dark matter interactions [2]. Dark matter of similar mass and nuclear cross-section was also recently suggested by the CoGeNT experiment [3, 4], the CDMS-Si experiment [5], and the CRESST experiment [6].

However, the dark matter interpretation of the DAMA modulation remains in question. Its tension with other experiments such as XENON [10], LUX [11] and KIMS [12] suggests the need for further investigation of the DAMA modulation. No experiment, however, has been able to test the DAMA experiment such that the interpretation is completely independent of the dark matter model chosen. Such a test is strongly desired by the dark matter community.

This controversy could potentially be resolved if the background in the DAMA singles rate (the rate of scintillation events occurring in only one crystal) could be mitigated. As shown in Fig. 1 (bottom right), the DAMA energy spectrum exhibits a peak around 3 keV$_{ee}$ [7], which is a strong indication of X-ray/Auger

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doi:10.1016/j.phpro.2014.12.028

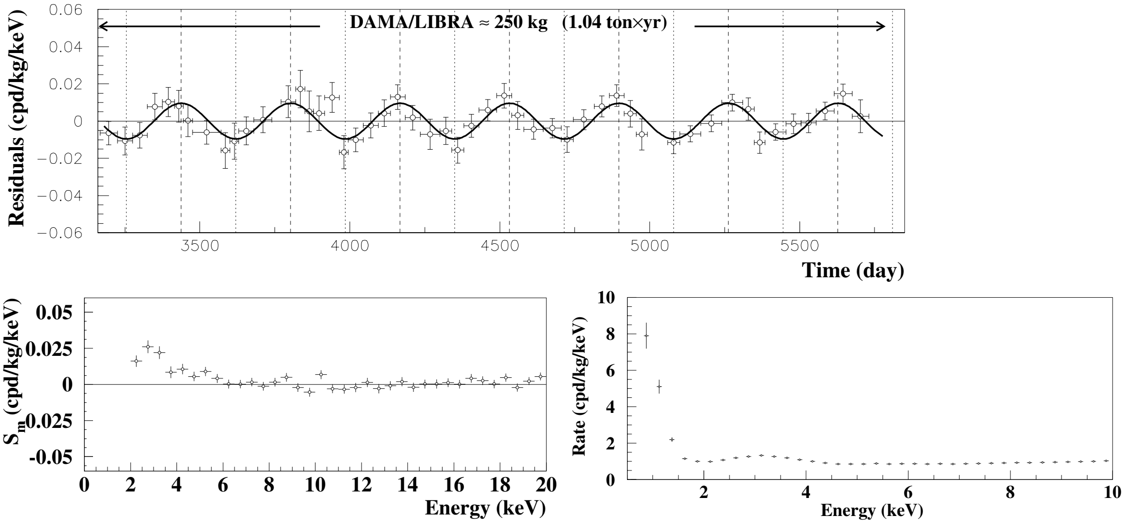

Fig. 1. **Top:** the annual modulation of the low energy (2-6 keV$_{ee}$) event rate in the DAMA/LIBRA experiment. **Bottom Left:** the modulation amplitude at different energies in DAMA/LIBRA. **Bottom Right:** The energy spectrum of events occurring in a single crystal in DAMA/LIBRA.

electron background from ^{40}K decays in the NaI(Tl) crystals[1]. The fact that this significant ^{40}K background shows up at the same energy as the largest modulation amplitude in DAMA (Fig. 1, bottom left) is significant.

2. SABRE (Sodium-iodide with Active Background REjection)

The SABRE (Sodium iodide with Active Background REjection) experiment seeks to conduct a direct test of DAMA through a number of innovations. The signature features are the development of ultra-high purity NaI(Tl) crystals and the rejection of the residual ^{40}K background (among others) using an active veto.

Based on our current progress described in the sections below, we believe that these goals are achievable. High-purity crystals can be developed using high-purity powders already produced in collaboration with industrial partners. Through these partnerships, we have made significant progress toward the development of new ultra-high purity crystal growth techniques. The active veto can be achieved with a liquid scintillator vessel based on a detector already developed for the DarkSide experiment. We believe such an experiment can provide a definitive test of the DAMA modulation in three years of running.

2.1. The Potential ^{40}K Background

The DAMA/LIBRA crystals contain trace amounts of ^{40}K (a 13 ppb average is reported in the literature [8]). When ^{40}K decays to ^{40}Ar, it produces a 1.46 MeV γ-ray at the same time as a possible 3 keV X-ray/Auger electron, as shown in Figure 2. If the γ-ray escapes the detector, the 3 keV deposition will become a source of background in the primary energy region of interest. Simultaneous, separate detection of these two signals, however, can be taken as a signature of ^{40}K decay and can be used to reject such backgrounds. DAMA suppresses some of the ^{40}K background by rejecting "multi-hit" events, in which more than one crystal sees a signal. However, the inefficiency of this technique is clearly indicated by the $\sim$3 keV$_{ee}$ peak in their energy spectrum.

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[1] DAMA reports an averaged ^{nat}K concentration of $\sim$13 ppb in their NaI(Tl) crystals [9].

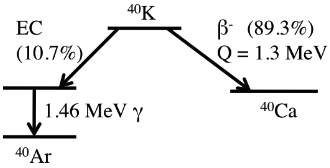

Fig. 2. ^{40}K decay scheme

2.2. The Veto Concept

Rather than rely solely on coincidence rejection between multiple crystal volumes, a dedicated detector surrounding the experimental apparatus can be used to detect radiation leaving the active dark-matter-sensitive volume. Such a detector, filled with liquid scintillator, can provide an active veto for events in the crystals that produce escaping radiation, as is the case in ^{40}K decay, as well as other radioactive backgrounds. An illustration of this principle is shown in Figure 3.

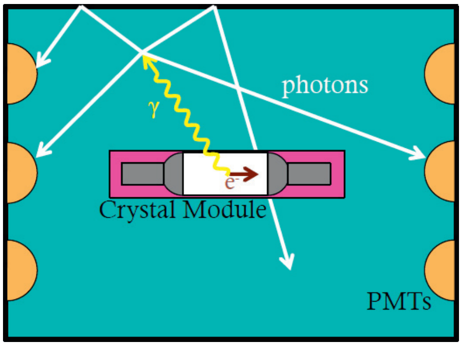

Fig. 3. An illustration of the veto concept as applied to ^{40}K decay (not to scale). When ^{40}K decays into ^{40}Ar, it produces a 3 keV x-ray/Auger electron with a corresponding 1.4 MeV γ ray. A liquid scintillator detector surrounding the crystal can observe the γ ray that would otherwise escape the system. These background events can be rejected.

2.3. Description of the Experiment

The current design of the SABRE experimental setup for one crystal is shown in Fig. 4, while the eventual design for a ~50-60 kg dark matter experiment is shown in 5 (left). Though initial tests will be conducted with a smaller crystal (1-2 kg), a larger-scale experiment will make use of larger, 8-10 kg crystals. Each crystal will be enclosed in a self-contained module consisting of the crystal itself and two low-radioactivity, high-quantum-efficiency photomultiplier tubes. The phototubes will be optically coupled to opposite sides of the crystal. These components will be sealed in a light- and air-tight, low-radioactivity, metal container. This container and its contents constitutes a single NaI detector module.

These NaI(Tl) crystal detectors will be installed in the center of a ϕ1.5 m×1.5 m cylindrical liquid scintillator veto detector that is shielded from environmental background with ~20-25 cm of passive steel or lead shielding. During a ^{40}K decay, if the accompanying 1.46 MeV γ-ray escapes the NaI(Tl) crystal module and gets recorded in the liquid scintillator detector, the associated ~3 keV$_{ee}$ feature in the NaI(Tl) crystal detector can be tagged and rejected. This veto can also be applied other internal radioactivity as well as external γ-ray backgrounds.

2.4. Experimental Plan

The current plan for the SABRE experiment is to operate in two phases. First, the goal is to grow ultra-high purity crystals and understand their intrinsic radioactivity. This will be done by using the active veto detector or the DarkSide-50 veto as a coincidence counter to measure the rate caused by impurities in the

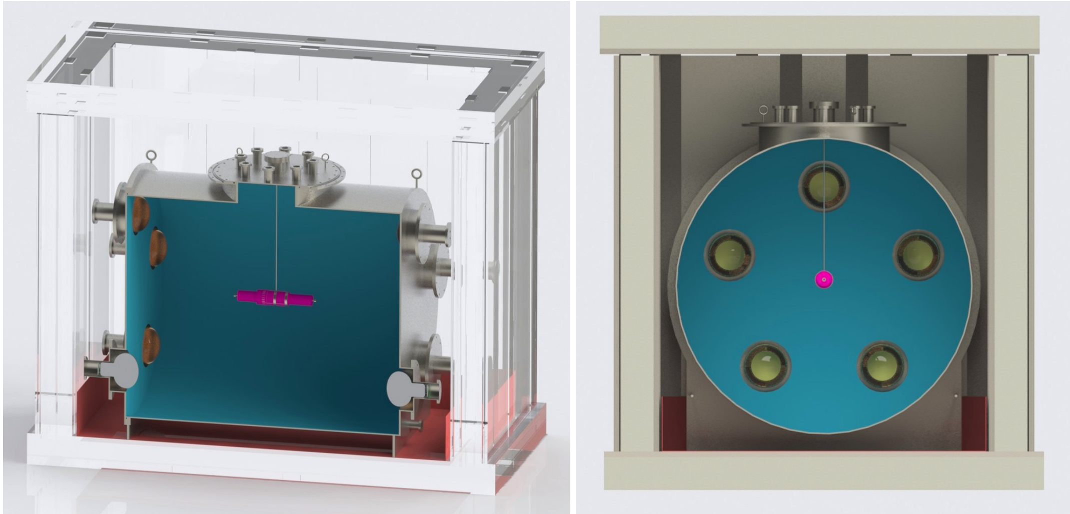

Fig. 4. Design for the SABRE experimental setup for one small (1-2 kg) crystal. Opposite faces of the crystal will be coupled to two 3” PMTs operated in coincidence. The PMT pair and crystal will be enclosed in an air-tight enclosure, which will be suspended in a liquid scintillator veto detector currently under construction. This detector will be outfitted with 10 8” R5912 Hamamatsu PMTs to detect the scintillation light. The scintillation detector will be surrounded in turn with lead and steel passive shielding.

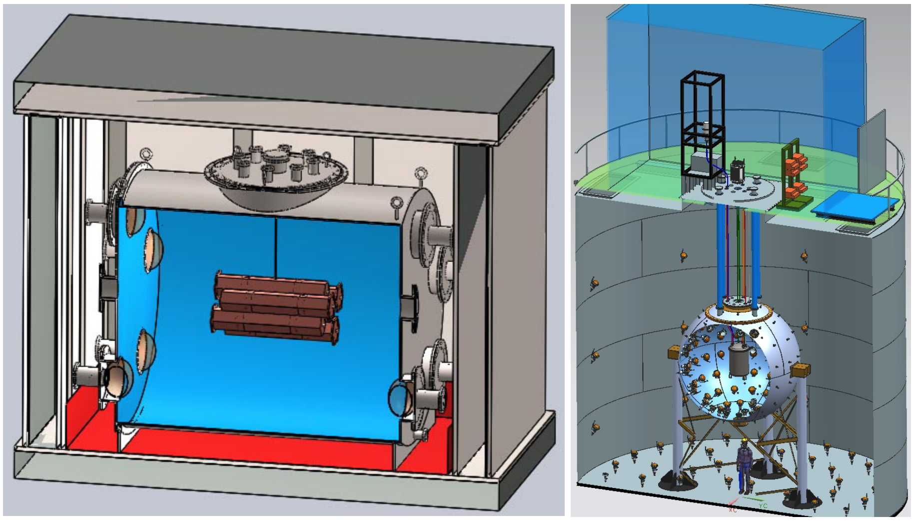

Fig. 5. **Left:** Design of the SABRE experimental setup. The liquid scintillator vessel is a ϕ1.5 m×1.5 m stainless steel cylinder containing $\sim$2 tons of liquid scintillator (in blue). The NaI(Tl) detectors (in brown) are installed in the center of the veto vessel, and 10 Hamamatsu 8” PMTs are used to collect the veto scintillation light. The whole setup is shielded from external backgrounds by $\sim$20-25 cm of passive shielding (in dark gray). **Right:** An illustration of the DarkSide-50 experiment. A ϕ4 m liquid scintillator detector (the sphere in the center) is contained inside a ϕ11 m×10 m water tank, which hosts the DarkSide-50 experiment. The SABRE NaI(Tl) crystal detectors can be installed between the DarkSide-50 TPC and the walls of the veto sphere. DarkSide-50 also has a number of facilities already in place, such as scintillator handling and purification systems, which can be shared with SABRE.

crystals. The second phase will be to conduct a dark matter measurement with 50-60 kg of target material in an underground setting, such as LNGS or SNOLab.

3. The NaI Powder

With industrial partners Sigma-Aldrich and Seastar-MV Laboratories, we initiated and helped to develop and test NaI powder with lower backgrounds than were previously available. The primary aim has been to reduce K levels below the 13 ppb seen by DAMA in their crystals [9]. We are also concerned with all backgrounds listed in [13], especially U, Th, and Rb, which all contribute to the flat background in the energy spectrum. With upgraded methods and purification procedures, Sigma Aldrich produced the first 50 kg sample of high purity NaI powder in August, 2010, which we found to have lower intrinsic radioactivity than standard powders. Since then, Sigma-Aldrich has made a high purity "Astro-grade" powder with a reported ^{nat}K level of 3.5 ppb. This powder has been used to grow test crystals (described in Sec. 4). We also have worked with MV Laboratories, a local subsidiary of Seastar Inc. that specializes in the production and testing of highly pure inorganics. They developed extremely pure sodium carbonate and hydriotic acid, the precursors for NaI, and also analytic techniques for quickly measuring K content at very low levels. MV Laboratories has reduced K content to 13 ppb. It is important to note that both powders have K concentrations comparable to or lower than that of DAMA's final crystals. Further purification is expected during the crystal growth process and through other methods being explored by our industrial partners. Purity levels of these powders are shown in Table 1

Table 1. Impurity levels in NaI powders developed by our collaborators

Impurity	DAMA	Sigma Aldrich "Astro-Grade"	MV Laboratories
K	<100 ppb	3.5 ppb	13 ppb
Rb	0.5 ppb in crystal, powder unreported	14 ppb	0.2 ppb
Th	20 ppt	<200 ppt	<1700 ppt
U	20 ppt	<100 ppt	<500 ppt

4. The Crystal Growth

The DAMA modulation on the order of 0.02 cpd/kg/keV$_{ee}$ makes the reduction of detector background imperative to a dark matter observation. Traces of radioactive isotopes in the crystal will be the leading source of background for SABRE. As has been discussed, ^{40}K in the crystal can significantly increase the background level in the energy region of interest, and isotopes like ^{238}U, ^{232}Th, and ^{87}Rb can contribute to a broader energy range as well.

To achieve a high sensitivity to the dark matter modulation signal, SABRE aims for background levels below that in the DAMA/LIBRA experiment. DAMA has a single interaction rate of $\sim$1 cpd/kg/keV$_{ee}$, with reported crystal radioactivity levels of 13 ppb ^{nat}K (average) and $\sim$1-10 ppt for U and Th [13]. With our collaborators, we are exploring high purity crystal growing methods in addition to our efforts with the starting material.

The SABRE crystals are being grown from the highly pure powders already available from our previous work with Sigma Aldrich and MV Laboratories. Additional work will be done to measure accurately, and to lower as much as possible, the concentrations of U, Th, and Rb in these powders.

In addition to radioactivity, other crystal characteristics also dramatically affect the apparatus's achievable sensitivity to dark matter. The scintillation yield and optical properties of the crystal are directly related to the detected signal amplitude, and thus to the achievable energy threshold of the experiment. Large crystal masses are also necessary for the experiment to achieve a high dark matter sensitivity. Due to light attenuation effects, longer crystals decrease the light yield, and crystals with large cross-section are preferred. We expect to grow NaI(Tl) crystals around ϕ 4"×10" with a total mass of 8-10 kg each. The Kyropoulos process is the preferred crystal growth method for large crystals, and will be used for SABRE.

To develop methods for growing ultra-low background NaI(Tl) crystals, SABRE partnered with Radiation Monitoring Devices (RMD) to research further purification of the NaI powder and procedures for growing NaI(Tl) crystals. Initial research was conducted with the vertical Bridgman crystal growing method. This method was explored by RMD to understand the influence of the crystal growth process and the crucible itself on the final crystal purity. Growths with normal purity powder showed significant purification for K (4-5x to the level of 300 ppb). RMD has also achieved preliminary success in growing NaI(Tl) crystals from high purity NaI powder with vertical Bridgman growth. These crystals (shown in Figure 6) show strong scintillation properties and low radioactivity.

RMD has already grown several normal-purity NaI crystals using Kyropoulos systems, the preferred method for the growth of large crystals. We have provided them with a platinum and a synthetic fused silica Kyropoulos crucible for future high-purity growths. RMD will also employ other purification methods to further reduce potassium and other radio-impurities in the powder before crystal growth.

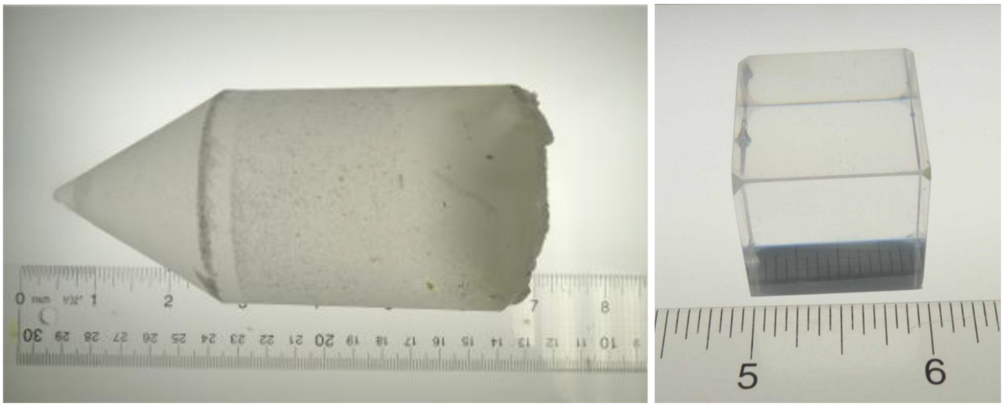

Fig. 6. **Left:** NaI(Tl) ingot grown by vertical Bridgman method at RMD; **Right:** The resulting cut and polished crystal.

5. The Liquid Scintillator Veto

The primary considerations determining the effectiveness of the liquid scintillator detector are the stopping power of the veto and the light collection efficiency. The stopping power of the veto is primarily determined by the detector size. Simulations have shown that 50 cm of liquid scintillator can detect $\sim$95% of $\sim$1.4 MeV γ-rays passing the volume, and we have designed a ϕ1.5 m×1.5 m cylindrical liquid scintillator veto for the NaI(Tl) detectors with a similar γ-ray detection efficiency. The veto design is shown in Fig. 5 (left); it will contain $\sim$2 tons of the liquid scintillator linear alkylbenzene (LAB). Ten 8” Hamamatsu R5912 PMTs arrayed on either side will collect the scintillation light. To increase the light collection of the veto detector, we will line all non-PMT internal surfaces with the reflector Lumirror, which has a reflectance of over 98% above 350 nm and was found to maintain its high reflectivity when immersed in liquid. Simulations that have been verified with the DarkSide-50 neutron veto detector predict a light yield of 0.22 p.e./keV$_{ee}$ for the SABRE veto detector.

In addition to rejecting detector radioactivity, the liquid scintillator detector can also provide a measurement of various residual backgrounds in the system. Use of the liquid scintillator detector in coincidence with the crystal detectors will provide quick (on the order of a few weeks) feedback on the ability of our crystal purification methods to reduce K, U, and Th.

5.1. The DarkSide-50 Neutron Veto Detector

The working DarkSide-50 neutron veto detector, shown on the right in Fig. 5, may also be used for the SABRE experiment. This veto detector is a ϕ 4 m sphere with 110 R5912 Hamamatsu 8” PMTs. It uses a combination of pseudocumene (PC), trimethylborate (TMB), and 2,5-diphenyloxazole (PPO) as the scintillator, and is lined with the Lumirror reflector. The light yield of this detector has been measured to be 0.52 photoelectrons/keV$_{ee}$, giving it a high γ-ray detection efficiency (>99%) down to 30 keV$_{ee}$. Outside, the neutron veto detector is shielded by an active water Cherenkov veto detector (ϕ11 m×10 m), which also provides sufficient passive shielding power for our purposes. Due to these advantages, the DarkSide-50 neutron veto is well suited to the deployment of a number of crystal dark matter detectors within its volume.

The DarkSide-50 veto detector is outfitted with 4 large tubes leading up to the clean room outside of the water shielding. The tubes have a 6” inner diameter, allowing for the insertion of our large crystal modules. The full array of crystal modules can be lowered into the veto detector for initial tests or for a dark matter run.

6. Expected Background

To make a definitive test of the DAMA/LIBRA result over an operational period of a few years, a thorough understanding of our backgrounds is imperative. We expect the primary backgrounds to come from the following sources:

1. K, Th, U, and Rb in the crystal
2. The photomultiplier tubes (both in the crystal modules and in the liquid scintillator detector, primarily from the plate for the feedthrough pins)
3. The crystal housing (the bulk material, the electrical feedthroughs, reflectors, etc.)
4. The steel vessel for the liquid scintillator
5. The passive shielding outside the veto
6. External background (both from the surrounding rock and cosmogenics)

We have made an estimation of the contributions of these sources to the experimental background using two GEANT4 simulations for both phases of the experiment: an initial measurement of the ^{40}K content in the crystal using the liquid scintillator detector as a coincidence counter, and a dark matter measurement using the scintillator detector as an active veto. In both simulations, we assumed crystal impurity levels similar to DAMA, typical radioactivity from the vessel stainless steel, and measured room backgrounds at LNGS. Both simulations used the geometry of the dedicated liquid scintillator veto detector.

6.1. NaI(Tl) K Measurement

In the first phase of the experiment, large crystals will be developed. To provide quick and accurate feedback on our purification methods, we will use SABRE as a gamma-counter to measure the K levels in the crystals. When operating the liquid scintillator detector as a coincidence counter for this purpose, the most significant background is from external sources. To bring the background down to a rate wherein we can be sensitive to the levels of potassium seen in DAMA, we calculate that a 10^4 rejection from passive shielding is necessary. We have measured the background activity from both the 3” PMTs that will be coupled to the crystal, and the 8” tubes that will measure the veto detector scintilation. While the activities of other sources are not yet measured, we have estimated some “typical” values in our analysis, motivated by other experiments. In the case of the crystal backgrounds other than K, we assume values similar to DAMA. For the steel vessel, we assume values similar to those seen by other experiments in their stainless steel.

For a concentration of ~10 ppb K in the crystal, we expect a ^{40}K rate of around 1 cpd/kg. From Table 2 it can be seen that a background below this level can be achieved.

6.2. Dark Matter Measurement

We performed an estimate of the background for a dark matter measurement using a Monte Carlo simulation of a small, 2 kg crystal and assuming DAMA-level backgrounds from the crystals. This simulation demonstrates liquid scintillator veto detector’s high rejection efficiency. The crystal ^{40}K events, veto PMTs,

Table 2. Background estimate for a measurement of the ^{40}K content in the NaI(Tl) crystals using the liquid scintillator detector as a coincidence counter. This estimate is from a GEANT4 simulation of a single 2 kg crystal at the center of the liquid scintillator veto.

Background Source	Expected or Measured Activity	Expected Background Rate (cpd/kg)
Crystal U & Th	$\mathcal{O}(10)$ ppt (expected)	~0.01
Crystal PMTs	$\mathcal{O}(10)$ mBq/tube K, Th, U, Co (measured)	0.19
Liquid Scintillator PMTs	$\mathcal{O}(10)$ mBq/tube K, Th, U, Co (measured)	0.06
Steel Vessel	$\mathcal{O}(10)$ mBq/kg K, $\mathcal{O}(1)$ mBq/kg Th, U, Co (expected)	0.1
Shielding	$\mathcal{O}(0.1\text{-}10)$ mBq/kg K, Th, U, Co (expected)	0.1
External (assuming 10^4 rejection from passive shielding	$\mathcal{O}(0.01)$ γ/m^2/s (expected)	0.21
TOTAL:		0.67

steel vessel, and external backgrounds, in particular, are rejected at a high rate, leaving U and Th in the crystal as the dominant backgrounds. Further efforts to lower these impurities can drastically reduce SABRE's total background rate.

We conducted GEANT4 simulations to study the effectiveness of the liquid scintillator veto and to predict the background level in the SABRE experiment for a small crystal (1-2 kg) run. Of ^{40}K events depositing 2-4 keV in the primary crystal, nearly 90% are rejected either by the liquid scintillator veto or by a coincident event in another crystal. This leads to a very high suppression of the ^{40}K background in the SABRE experiment. Figure 7 shows a conservative prediction of the SABRE background spectrum for a small crystal compared with the DAMA singles spectrum. The overall expected SABRE background level is estimated to be ~2 times lower than the DAMA/LIBRA flat singles rate [2].

With the ^{40}K background highly suppressed, the U and Th radioactivity begins to dominate the residual background spectrum. Through our collaborations with Sigma Aldrich, MV Laboratories, and RMD, it is very likely for SABRE to achieve a lower radioactivity level in K, as well as from U and Th, than what is simulated. Planned measurements of the radioactivity in the first radio-pure crystals produced will better clarify the expected background stemming from all of these radioactive isotopes.

7. Physics Implications

With the conservative predicted background rate of around 0.4 cpd/kg/keV$_{ee}$from our Monte Carlo simulations, we proceeded to simulate a modulation analysis of a 3-year run of the SABRE experiment in two scenarios: 1) if the DAMA modulation is due to detector-specific background interactions and 2) if the DAMA-observed modulation is due to dark matter interactions. In each simulation we generated 3 years of hypothetical SABRE data from either our expected background rate in case 1, or a modulating dark matter interaction rate[3] on top of the expected SABRE background rate in case 2. From these data sets we extracted a modulation amplitude using a likelihood fit where the modulation phase and period are fixed to the DAMA values. The fitted modulation amplitude and its uncertainty were then used to choose between

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[2] We comment that our Geant4 simulations using the DAMA detector geometry and the DAMA-reported background radioactivity seem to underestimate the DAMA background. An unknown source of background may exist and could similarly affect the SABRE experiment.

[3] This rate is calculated based on the dark matter parameters optimized for DAMA in the standard halo model.

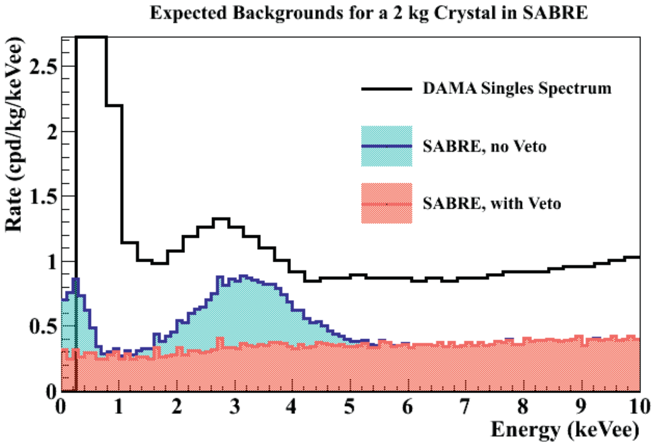

Fig. 7. Expected Backgrounds for a single 2 kg crystal dark matter measurement in SABRE with and without the liquid scintillator veto detector, as compared with the DAMA single hit rate. The 3 keV$_{ee}$ feature due to the decay of ^{40}K is drastically reduced by the veto.

the DAMA modulation model and the alternative zero modulation model using a hypothesis test. In either case, the SABRE modulation analysis can confirm or refute DAMA with $>3\sigma$ confidence level in $>98.5\%$ of the simulations, provided the detector performance is sufficiently stable. We comment that the confidence will improve if a lower background than what is assumed in this analysis is achieved. Such a low radioactive background level will also enhance SABRE's sensitivity to dark matter interactions. Therefore, even if SABRE refutes the dark matter claim of DAMA, it will be able to explore the regime of light WIMP dark matter at high sensitivity and contribute to the dark matter search community.

8. Future Plans and Conclusions

We expect to install the SABRE experimental setup at LNGS, either using the dedicated liquid scintillator veto detector, or taking advantage of the working DarkSide-50 veto detector. At present, our plan is to use the DarkSide-50 veto for initial measurements, and then either DarkSide-50 or our own liquid scintillator veto detector for a separate dark matter measurement, which will initially begin with a target mass of 50-60 kg. The compact size of the dedicated liquid scintillator detector also makes it possible to relocate SABRE to the deeper SNOLab site if lower cosmic ray background than that of LNGS is desired.

With a 50-60 kg array of NaI(Tl) crystals, active rejection of backgrounds, and possibly more radio-pure crystals and detector components, SABRE will provide a direct test of the DAMA/LIBRA measurement, but is also designed to improve upon DAMA/LIBRA. The production of the liquid scintillator veto detector and the crystals is underway. From the progress that has been made thus far, we believe the SABRE experiment can achieve a background rate lower than that of DAMA.

References

[1] R. Bernabei *et al*, Phys. Lett. **B 450** 449 (1999).
[2] R. Bernabei *et al*, arxiv:1308.5109.
[3] C. E. Aalseth *et al* (CoGeNT Collaboration), Phys. Rev. Lett. **106**, 131301 (2011).
[4] C. E. Aalseth *et al* (CoGeNT Collaboration), Phys. Rev. Lett. **107**, 141301 (2011).
[5] R. Agnese *et al* (CDMS Collaboration), arxiv:1304.4279, accepted by Phys. Rev. Lett..
[6] G. Angloher *et al*, Eur. Phys. J. **C 72** 1971 (2012).
[7] R. Bernabei *et al*, Eur. Phys. J. **C 56** 333 (2008).
[8] R. Bernabei *el al*, arxiv:1210.6199v1
[9] R. Bernabei *et al*, arxiv:1210.5501.
[10] J. Angle *et al* (XENON10 Collaboration), Phys. Rev. Lett. **107**, 051301 (2011).

Table 3. Background estimate for a dark matter measurement using a GEANT4 simulation of a single 2 kg crystal at the center of the liquid scintillator veto.

Background Source	Expected or Measured Activity	Expected Background Rate with Veto	Veto Rejection Efficiency
Crystal K	10 ppt (expected)	~0.05 cpd/kg/keV	91%
Crystal U & Th	10 ppt each (expected)	~0.2 cpd/kg/keV	4%
Crystal PMTs	$\mathcal{O}(10)$ mBq/tube K,Th,U,Co (measured)	1E-3 cpd/kg/keV/tube	83-98%
Liquid Scintillator PMTs	$\mathcal{O}(10)$ mBq/tube K, Th, U, Co (measured)	<5E-6 cpd/kg/keV/tube	>93%
Steel Vessel	$\mathcal{O}(10)$ mBq/kg K, $\mathcal{O}(1)$ mBq/kg Th, U, Co (expected)	<0.01 cpd/kg/keV	>93%
Shielding	$\mathcal{O}(0.1\text{-}10)$ mBq/kg K, Th, U, Co (expected)	<0.06 cpd/kg/keV	>93%
External (assuming 10^4 rejection from passive shielding	$10,000\gamma/\mathrm{m}^2/\mathrm{s}$ (expected)	<7E-3 cpd/kg/keV	78%
TOTAL:		0.39 cpd/kg/keV	84%

[11] D.S. Akerib *et al* (LUX Collaboration), arxiv:1310.8214.
[12] S. C. Kim *et al* (KIMS Collaboration), Phys. Rev. Lett. **108**, 181301 (2012).
[13] R. Bernabei *et al*, Nucl. Instrum. Methods **A 592** 297 (2008).