First measurements with a NaI(Tl) crystal for the SABRE experiment

A. Mariani[1,2]

[1]Gran Sasso Science Institute (GSSI), Viale F. Crispi, 7, I-67100, L'Aquila (AQ), Italy
[2]INFN-Laboratori Nazionali del Gran Sasso, Via G. Acitelli, 22, I-67100, Assergi (AQ), Italy

E-mail: ambra.mariani@gssi.it

M. Antonello, E. Barberio, T. Baroncelli, J. Benziger, L.J. Bignell, I. Bolognino, F. Calaprice, S. Copello, D. D'Angelo, G. D'Imperio, I. Dafinei, G. Di Carlo, M. Diemoz, A. Di Giacinto, A. Di Ludovico, W. Dix, A. R. Duffy, E. Hoppe, A. Ianni, S. Krishnan, G.J. Lane, I. Mahmood, P. McGee, J. Mould, F. Nuti, D. Orlandi, V. Pettinacci, L. Pietrofaccia, S. Rahatlou, A.E. Stuchbery, B. Suerfu, C. Tomei, P. Urquijo, C. Vignoli, M. Wada, A. Wallner, A.G. Williams, M. Zurowski (The SABRE Collaboration).

Abstract. SABRE is a dark matter direct detection experiment aiming to measure the annual modulation of the dark matter interaction rate in NaI(Tl) crystals. SABRE focuses on the achievement of an ultra-low background rate operating high-purity NaI(Tl) crystals in a liquid scintillator veto for active background rejection. Moreover, twin experiments will be located in both Northern and Southern hemispheres (Italy and Australia) to disentangle any possible contribution from seasonal or site-related effects.
In this article the results of the first measurements with a NaI(Tl) crystal for the SABRE experiment performed at LNGS are presented.

1. Introduction

For decades, direct dark matter detection experiments have been searching for WIMP dark matter [1] obtaining null results, except for the DAMA/LIBRA experiment located at Laboratori Nazionali del Gran Sasso (LNGS). DAMA operates an array of ∼250 kg of NaI(Tl) crystals and observes an annual modulation of the interaction rate with a statistical significance of 12.9σ [2]. Experiments with different targets seem to exclude the interpretation of the DAMA signal as due to spin-independent dark matter nuclear scattering in the standard WIMP galactic halo hypothesis. On the other hand, existing experiments using NaI crystals have not achieved sufficiently low background to carry out a model independent verification of DAMA/LIBRA within a reasonable amount of time.

2. The SABRE strategy

The SABRE experiment plans to use NaI(Tl) scintillator to measure the annual modulation of dark matter interaction rate [3] and focuses on the achievement of an ultra-low background in

the energy region of interest for dark matter searches ([1 - 6] keV$_{ee}$ for NaI(Tl) detectors). It has four key features: development of ultra-high purity NaI(Tl) crystals, low energy threshold, active veto and dual location. Indeed, the dominant background is due to the crystal intrinsic radioactivity and it is the hardest to suppress. To keep the contaminants at a very low level Princeton University (PU), together with the industrial partner Radiation Monitoring Devices (RMD), have developed a specific ultra-clean crystal growth method which demonstrated a reduction of the impurities in the crystal with respect to the NaI powder [4].
As the modulation amplitude is larger at smaller energies it is also important to reach a low energy threshold. So, in order to maximize the light collection, low radioactivity and high quantum efficiency Hamamatsu R11065-20 3" PMTs directly coupled to the crystal with optical gel are used. Moreover, the crystals will be surrounded by liquid scintillator (active veto) to tag as background those signals with simultaneous energy depositions in the veto and the crystal. Finally, SABRE will have two identical detectors at LNGS and at the Stawell Underground Physics Laboratory (SUPL) to distinguish seasonal effects (reverse phase in opposite hemispheres) from dark matter signal (same phase).

3. The NaI-033 crystal and its characterization

The crystal NaI-033 was grown in a joint effort by PU and RMD using the vertical Bridgman method [5]. An octagonal crystal of mass 3.4 kg was obtained after cut and polishing. The average K concentration measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is ∼4 ppb [4], i.e. three times lower than DAMA crystals (13 ppb) [6] and nine times lower compared to other NaI(Tl) experiments such as ANAIS-112 (32 ppb) [7] and COSINE-100 (42 ppb) [8]. In mid-May 2019, this crystal designated NaI-033 coupled to two PMTs was assembled into the copper enclosure in nitrogen atmosphere inside a dedicated glove box at Princeton University. The assembled detector module was then shipped to Italy by boat to reduce cosmogenic activation, and arrived at LNGS Hall B on August 6th, 2019.
The Hall B area hosts a passive shielding made of low radioactivity copper (5-10 cm) and lead (17.5 cm). It is enclosed in an anti-radon box, that can be sealed and flushed with nitrogen, if needed (Figure 1). The characterization measurements started a few days after the arrival of the crystal at LNGS and the preliminary analysis presented here refers to the first 19 days.

3.1. Energy resolution and light yield

The light yield and the energy resolution of the crystal have been measured by placing a ^{241}Am source next to the detector module (Figure 2). We find a light yield of 11 ph.e./keV and an energy resolution of 12.3% at 59.5 keV.

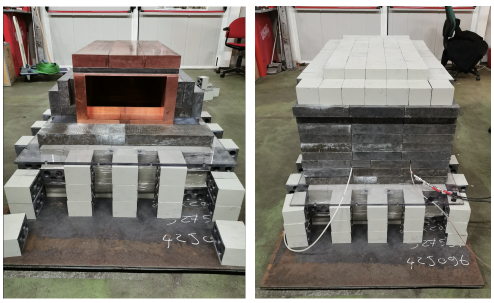

Figure 1. SABRE Hall B test setup with the external lead shield partially opened (left) and closed (right).

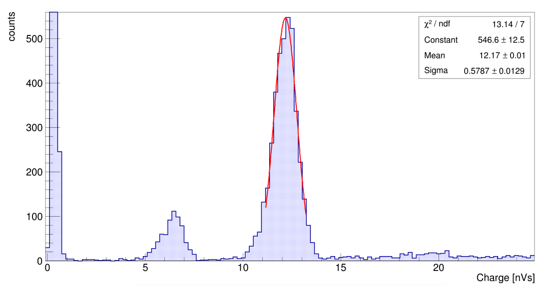

Figure 2. Measurement of NaI-33 light yield and energy resolution with a ^{241}Am source.

3.2. Current alpha rate

Alpha events have been selected using the pulse amplitude-weighted mean-time $\tau = \frac{\sum_i h_i t_i}{\sum_i h_i}$, where h_i is the height of the scintillation pulse at time t_i and summation is over 600 ns since the start of the pulse. We select alpha events with a linear cut in the mean-time vs. energy plane (Figure 3), observing a rate of (0.48 ± 0.01) mBq/kg.

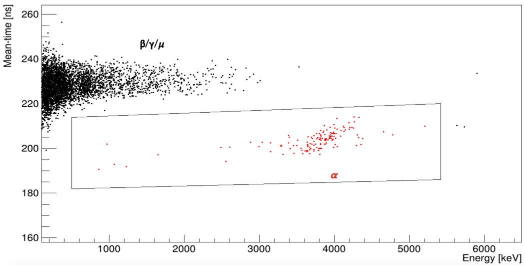

Figure 3. Selection of alpha events (red) in the mean-time vs. energy plane.

3.3. Bi-Po rates

The activity of ^{226}Ra (from ^{238}U chain) and ^{228}Th (from ^{232}Th chain) can be estimated by counting Bi-Po event pairs in both chains. Bi-Po event pairs are easily taggable as beta and alpha events occurring in time correlation (Figure 4 shows an example). With this method we measure activities of (5.4 ± 0.9) μBq/kg and (1.6 ± 0.5) μBq/kg for ^{226}Ra and ^{228}Th, respectively. Summing the alpha contributions from the two chain segments, we obtain a total of 0.03 mBq/kg. This indicates that the most part (0.45 ± 0.02 mBq/kg) of the alpha activity is dominated by ^{210}Po from a ^{210}Pb contamination out of equilibrium.

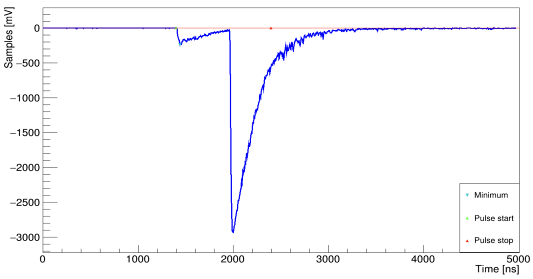

Figure 4. An example of ^{212}Bi -^{212}Po candidate (from ^{232}Th chain).

4. Conclusions

In order to test the interpretation of the DAMA signal, a new high sensitivity and low background measurement with NaI(Tl) crystals is needed. In this article, have been presented the first underground measurements with the NaI-033 crystal for the SABRE experiment, which presents the lowest K level ever achieved in NaI crystals and a promising low level of ^{210}Pb among currently-running NaI(Tl) detectors.

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