Status and prospects of SABRE North

Claudia Tomei, INFN Sezione di Roma
on behalf of the SABRE North Collaboration

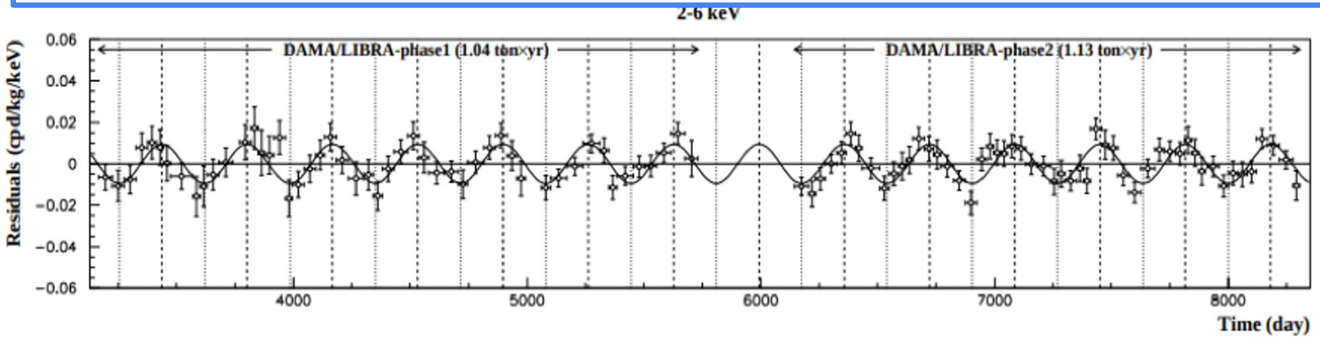
ICHEP 2022, Bologna July 6-13

see poster from Mike Mews: “The SABRE SOUTH experiment at the Stawell Underground Physics Laboratory” for more details on SABRE South

What is SABRE

- SABRE is an experiment to search for galactic dark matter (DM) through the annual modulation effect and to perform a model-independent test of the long-standing DAMA result
- SABRE is based on NaI(Tl) scintillating crystals and focuses on the achievement of an **ultra-low background** in the energy region of interest for DM search.

DAMA/LIBRA experiment @ LNGS modulation (phase1 + phase2): total exposure 2.17 ton x yr



Background ~1 cpd/kg/keV
Modulation: 0.0095 cpd/kg/keV
Modulation significance 11.9σ C.L.

Nuclear Physics and Atomic Energy 19 (2018) 307

Experiments using different target materials seem to exclude the dark matter interpretation of DAMA, at least in the standard WIMP framework and galactic halo hypothesis.
Currently running experiments using the same target (ANAIS-112 and COSINE-100), have not yet reached the **ultra-low background** and sensitivity achieved by DAMA.

SABRE: a dual site experiment

The ambitious program of SABRE foresees two detectors in two underground locations in the two Earth's hemispheres:

- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

STAWELL UNDERGROUND PHYSICS LAB

SABRE NaI(Tl) high purity crystals

The background in the 1-6 keV energy region of interest (ROI) for dark matter search is mostly due to crystal intrinsic contaminants, such as ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, ^{210}Pb.

The main R&D effort of SABRE was focused on the development of high purity NaI(Tl) scintillating crystals.

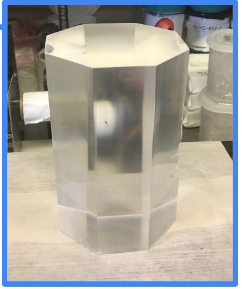
Phys. Rev. Res 2 (2020) 1, 013223

Several industrial partners involved:

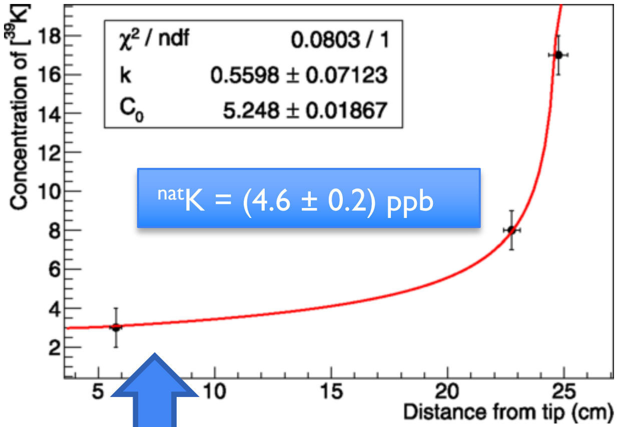
- ultra-high purity NaI powder (Astro Grade) with potassium levels consistently lower than 10 ppb and 1 ppt upper limit on U/Th content, in collaboration with Sigma Aldrich, now Merck;
- clean growth procedure using the vertical Bridgman-Stockbarger technique, where the powder is placed inside a sealed ampoule, in collaboration with Radiation Monitoring Devices, Inc (RMD).

NaI-31 - Mass 3 kg after polishing

NaI-33 - Mass 3.4 kg after polishing



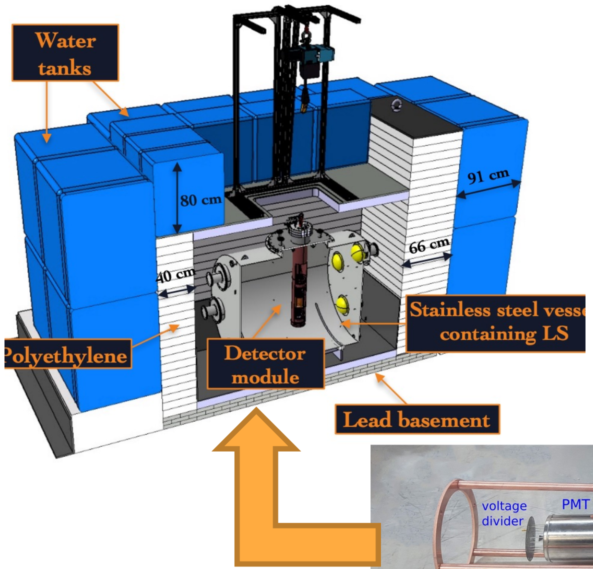
^{39}K distribution in NaI-33 (extrapolated from ICP-MS measurements)



lowest potassium level ever achieved

SABRE Proof of Principle (PoP)

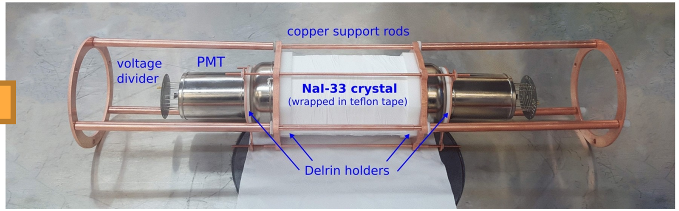
The SABRE PoP was commissioned between May and July 2020 and took data @ LNGS until September 2020. The **goal** was to assess the radio-purity of SABRE NaI(Tl) crystals and test the performances of an active veto.



Main features:

- one SABRE detector module consisting of a NaI(Tl) crystal wrapped with PTFE directly coupled to 2 PMTs in a copper enclosure;
- 2 ton liquid scintillator (LS) active veto;
- passive shielding made of polyethylene and water.

The PoP in Hall C @LNGS



Despite the short acquisition time, several important results obtained.

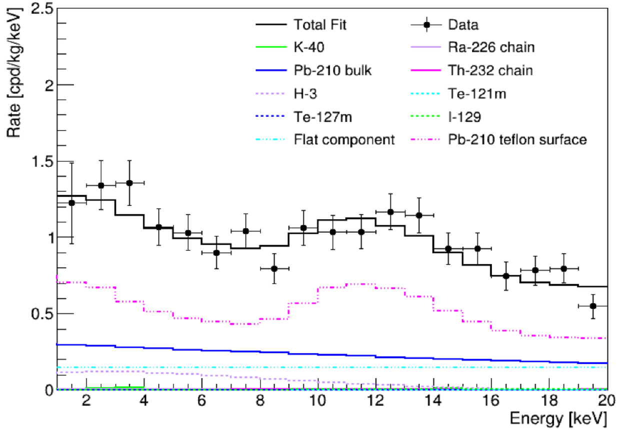
SABRE PoP results

Phys. Rev. D 104 (2021) 2, L021302

1) Measurement of potassium content with direct counting, exploiting coincidences between the crystal and the veto. Fully in agreement with ICP-MS results;

PoP setup sensitive to a ppb-level ^{nat}K contamination in the crystal: ^{nat}K < 4.7 ppb at 90% CL in NaI-33

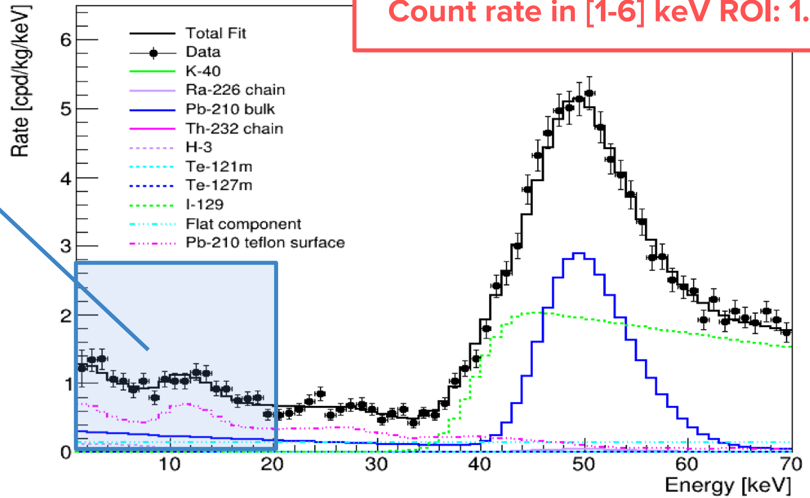
Efficiency corrected spectra



NaI-33 is the best crystal ever produced after DAMA/LIBRA in terms of radiopurity

2) Low energy analysis using a cut-based selection of scintillation events;

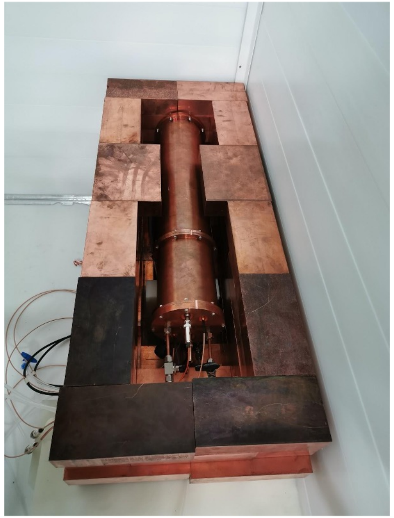
Count rate in [1-6] keV ROI: 1.20 ± 0.05 cpd/kg/keV



3) Background model of crystal NaI-33.

Geant4-based MC used to simulate radioactive decays of the main background sources.

New approach for the shielding: the PoP-dry



SABRE detector modules in a low radioactivity copper shield inside the passive PoP shielding.

In 2021 we modified the Hall C PoP setup for crystals characterization <u>without</u> the LS veto.

We removed the LS vessel and placed the NaI-31 and NaI-33 detector modules directly inside the PoP passive PE shielding. To compensate for the missing shielding power of the LS, we added (from inside to outside):

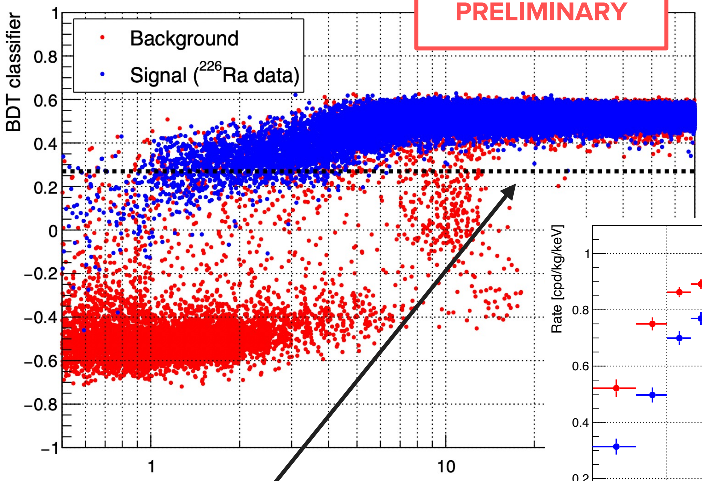
- Low radioactivity copper(10 cm on the sides and top, 15 cm below)
- PE slabs on the sides.

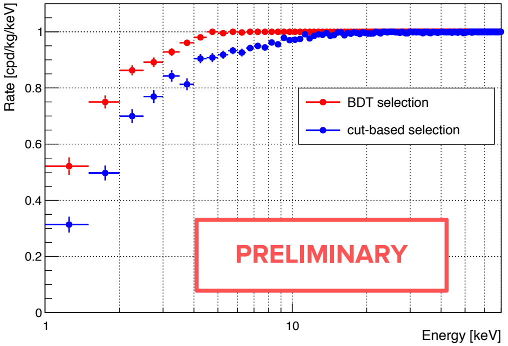
Data taking from March 2021 to June 2022 in Hall C @ LNGS

The PoP setup has just been decommissioned

SABRE PoP-dry results

1) Low energy analysis using a Boosted Decision Tree (BDT) approach to maximize the acceptance of scintillation events at very low energies while efficiently rejecting noise

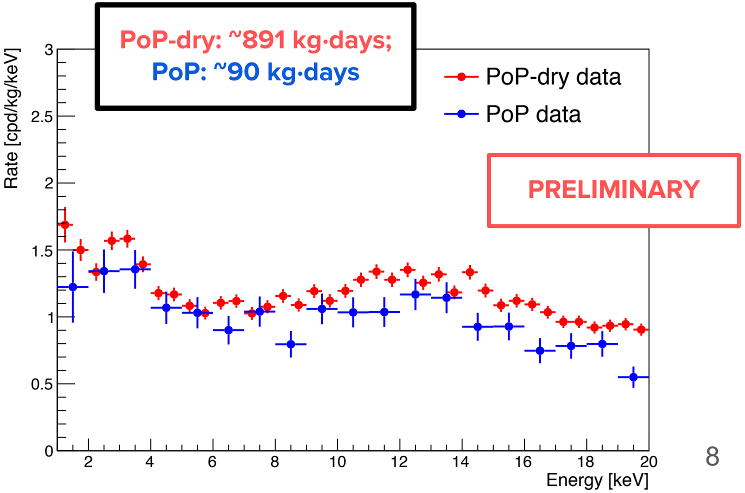




The BDT cut is chosen based on data acquired with a ^{226}Ra source to have an average event acceptance in the ROI > 90%.

2) The overall background rate in the ROI is comparable to that measured within the PoP setup

Count rate in [1-6] keV ROI: 1.36 ± 0.02 cpd/kg/keV



arXiv:2205.13876, submitted for publication

Results from background model (1)

The main features of the background components in NaI-33 have been addressed with both the PoP and the PoP-dry setup.

	PoP Exposure: ~90 kg·days		PoP-dry Exposure: ~891 kg·days	
Source	Activity [mBq/kg]	Rate in ROI [cpd/kg/keV]	Activity [mBq/kg]	Rate in ROI [cpd/kg/keV]
^{40}K	0.14 ± 0.01	0.018 ± 0.001	0.12 ± 0.02	0.096 ± 0.014
^{210}Pb (bulk)	0.41 ± 0.02	0.28 ± 0.01	0.46 ± 0.01	0.32 ± 0.01
^{226}Ra	(5.9 ± 0.6) x 10^{-3}	0.0044 ± 0.0005	(5.9 ± 0.6) x 10^{-3}	0.0049 ± 0.0005
^{232}Th	(1.6 ± 0.3) x 10^{-3}		(1.6 ± 0.3) x 10^{-3}	
^{3}H	(12 ± 7) x 10^{-3}	≤ 0.12	≤ 2 x 10^{-3}	≤ 0.004
^{129}I	1.34 ± 0.04	≤ 0.11 (*)	1.31 ± 0.01	
^{210}Pb (PTFE)	(1.1 ± 0.2) mBq	0.63 ± 0.09	(0.93 ± 0.04) mBq	0.51 ± 0.02
Flat component	-	0.10 ± 0.05		0.40 ± 0.02
Total		1.16 ± 0.10		1.34 ± 0.03

^{40}K contribution is sub-dominant due to the low activity

^{210}Pb (bulk) 2nd dominant background contribution

^{210}Pb (PTFE) Dominant background contribution

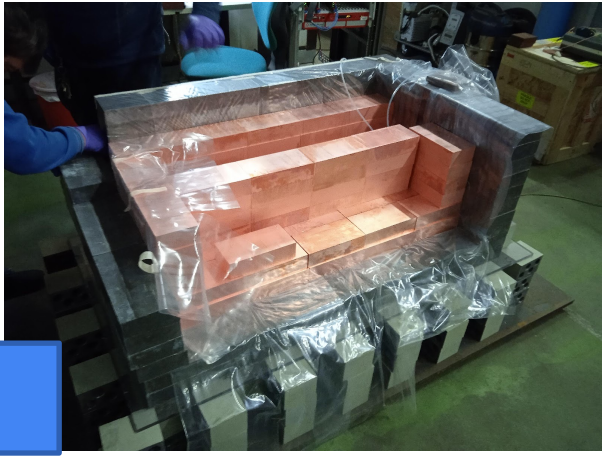
Flat component contribution is significant for the PoP-dry due to a not optimized shielding

Results from background model (2)

- Consistent results for internal background sources of NaI-33 crystal;
- The ^{40}K contribution has become sub-dominant due to the ultra high purity of NaI-33 in terms of potassium;
- The dominant contributions to the background rate in the ROI are not affected by the presence of the LS veto. This opens to a new shielding design for the physics phase of the SABRE North detector.

Two crucial steps ahead of us:

- Demonstrate the findings of our background model by replacing the PTFE reflector on NaI-33;
- Demonstrate the reproducibility of ultra high purity crystal production at the level of NaI-33 or even better (^{210}Pb bulk removal).



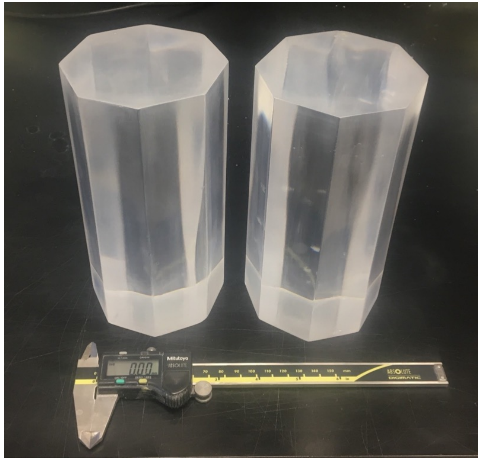
A new refurbished test facility is available in the SABRE experimental area in Hall B.

Upcoming activities

The glove box for SABRE crystals handling is being commissioned inside the clean room CR1 in Hall C.

It allows to work under nitrogen atmosphere: avoids radon and humidity.

- change reflector in NaI-33
- handling and assembling of new detectors

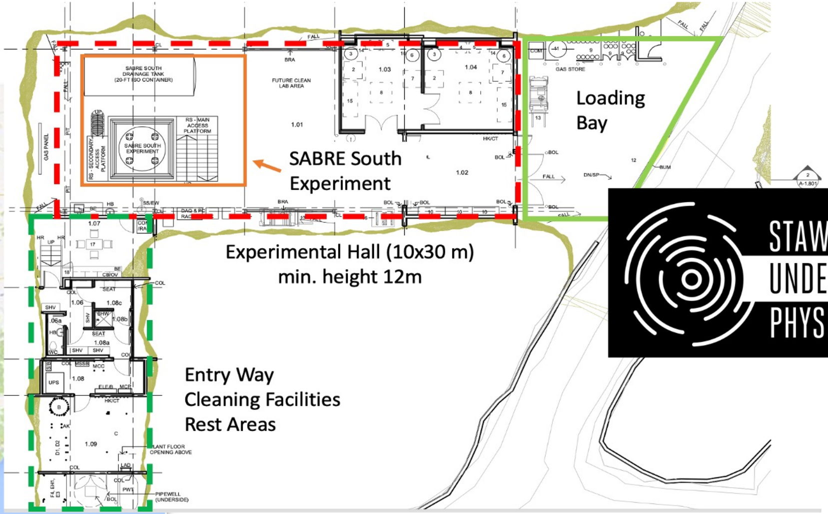


Two new crystals to test. Grown with Astrograde powder, cut and polishing and crucible preparation by RMD

- NaI-37 (~ 4.5 kg) naked, to be mounted into the copper enclosure (currently undergoing electropolishing at INFN LNL)
- NaI-35 ((~ 3.7 kg) purchased by our Australian Colleagues, in copper housing with quartz windows. Presently under measurement inside the Hall B setup.

Stawell Underground Physics Lab

- First deep underground laboratory in the Southern Hemisphere
  - 1025 m deep (2900 m water equivalent) with flat over burden
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia
  - Helical drive access
- Construction complete and operations will start in August/September 2022.



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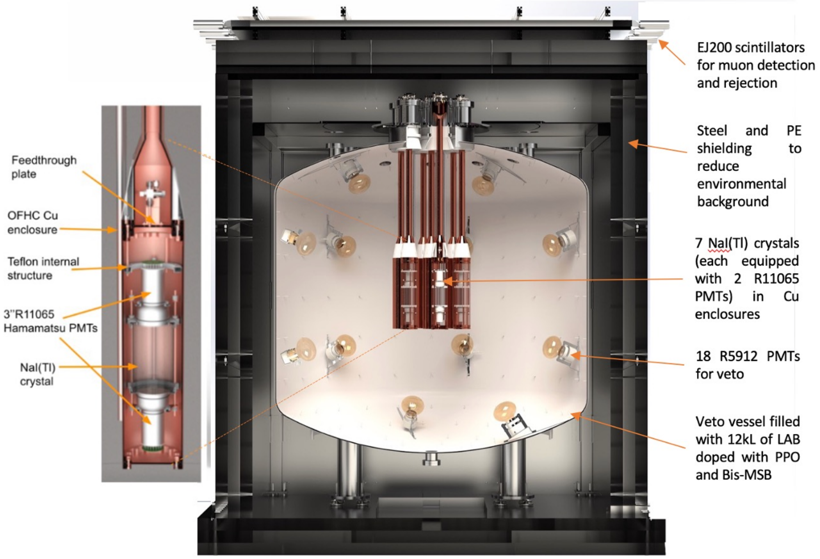
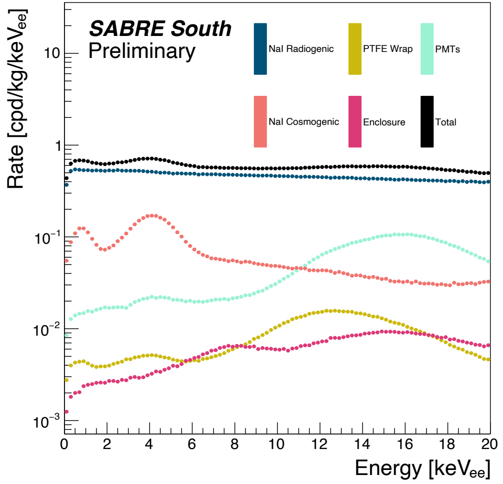
SABRE South status



Simulation studies of SABRE South background. Highest purity crystals and largest active veto: bkg ~ 0.7 cpd/kg/keV

more details in Mike Mews' poster



Assembly in SUPL will start in September 2022 and commissioning will start mid/late 2023.

- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system … **all ready**
- Crystal procurement is on-going
- One low background NaI(Tl) crystal in testing phase at LNGS.

http://arxiv.org/abs/2205.13849

SABRE North and South synergy

SABRE North and South detectors have common core features:

- Same detector module concept (Ultra-pure crystals and HPK R11065 PMTs)
- Common simulation, DAQ and software frameworks
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN

SABRE North and South detectors have different shielding designs:

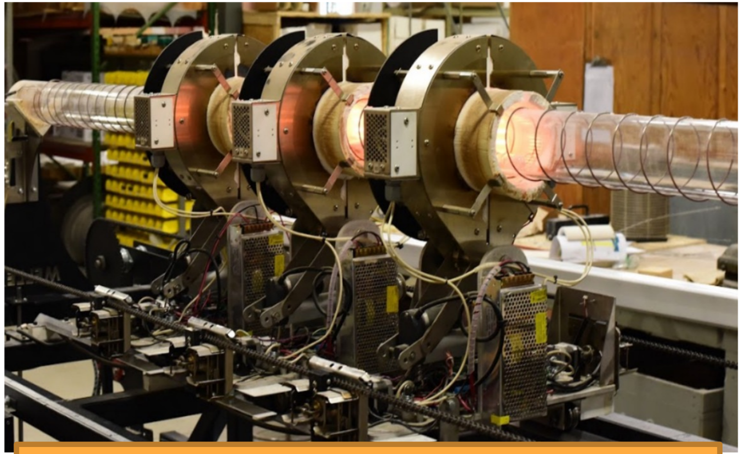
- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.

- SABRE South will be the first experiment in SUPL, the LS will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.

Future perspectives

Removing the background contribution from ^{210}Pb in PTFE would bring our rate to a level of ~ 0.5 cpd/kg/keV.

Zone refining is a purification method in which a narrow region of a crystal is melted, and this molten zone is moved along the crystal. The different segregation coefficients (k) of impurities in the molten vs the solid phase causes such impurities to concentrate at one end of the crystal and be removed.



Zone refining (ZR) equipment owned by PU developed in collaboration with Mellen Company

Test run performed in 2019: samples were taken from five successive sectors along the tube to perform ICP-MS measurements and estimate the purification factors.

Direction of the moving oven

Isotope	Impurity concentration (ppb)					
	Powder	S_1	S_2	S_3	S_4	S_5
^{39}K	7.5	<0.8	<0.8	1	16	460
^{208}Pb	1.0	0.4	0.4	<0.4	0.5	0.5
^{85}Rb	<0.2	<0.2	<0.2	<0.2	<0.2	0.7
^{24}Mg	14	10	8	6	7	140
^{133}Cs	44	0.3	0.2	0.5	3.3	760
^{138}Ba	9	0.1	0.2	1.4	19	330

Phys. Rev. Applied 16 (2021), 014060

ZR reduces ^{40}K and ^{87}Rb (from ^{39}K and ^{85}Rb measurements) to negligible levels, and ^{208}Pb by at least a factor of 2.5

ZR improvement + clean PTFE reflector would bring our background rate to a level of ~ 0.3 cpd/kg/keV

Conclusions

- The SABRE PoP and PoP-dry setups have concluded their data taking operating the best SABRE North crystal NaI-33
  - The PoP demonstrated a background level of 1.2 cpd/kg/keV with the liquid scintillator veto
  - The PoP-dry demonstrated a background level of 1.36 cpd/kg/keV without the liquid scintillator veto
  - Breakthrough in terms of radio-purity after the DAMA/LIBRA experiment.

- Thanks to the NaI-33 background model, the main background sources have been identified as a ^{210}Pb contamination in the crystal bulk and especially in the PTFE reflector wrapped around the crystal.

- At the level of crystal internal contaminations demonstrated by NaI-33, the active veto is no longer a crucial feature to achieve a background rate lower or comparable to that of DAMA/LIBRA.

- An array of crystals grown after ZR and wrapped with a clean PTFE reflector could push the background below the DAMA/LIBRA still unmatched level down to ~0.3 cpd/kg/keV, paving the way to a definitive test of the DAMA/LIBRA finding with an ultra low background NaI(Tl) detector.

Acknowledgements

SABRE North

Pacific Northwest NATIONAL LABORATORY

PRINCETON UNIVERSITY

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

UNIVERSITÀ DEGLI STUDI DI MILANO

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

SABRE South

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY of ADELAIDE

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government

Australian National University

ANSTO Science. Ingenuity. Sustainability.

Backup

Summary results from SABRE PoP crystals

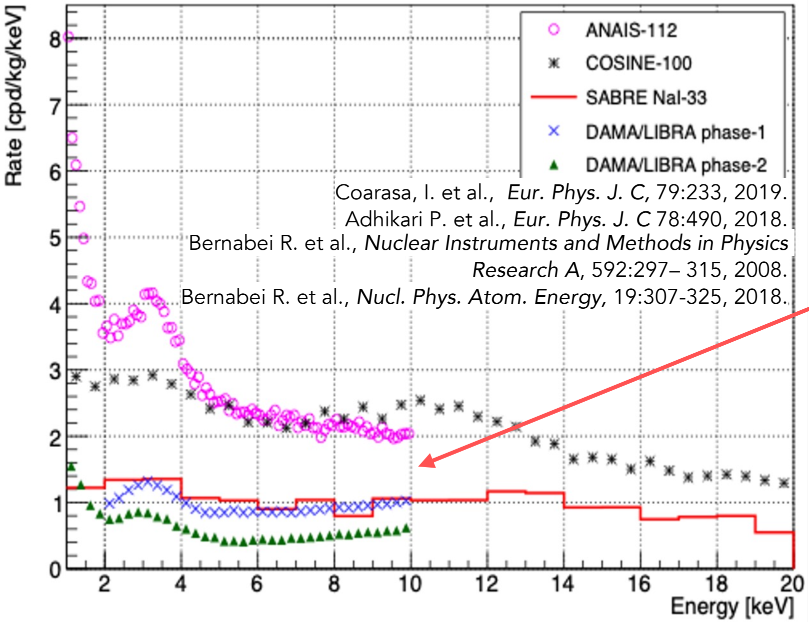
- Light yield (LY) and energy resolution (FWHM/E) competitive with other NaI(Tl)-based experiments;
- Alpha rate still higher than DAMA, but lower than ANAIS and COSINE crystals.

	NaI-31	NaI-33	DAMA/LIBRA crystals	ANAIS crystals	COSINE crystals
LY [phe/keV]	9.1 ± 0.1	12.1 ± 0.2	6-10	15	15
FWHM/E @59.5 keV	14.1%	13.2%	15.8%	11.2%	11.8%
^{nat}K [ppb]	17.7 ± 1.1	4.6 ± 0.2	< 20	17-43	17-82
^{3}H [mBq/kg]	-	0.012 ± 0.007	< 0.09	0.09-0.20	0.05-0.12
Alpha rate [mBq/kg]	1.02 ± 0.07	0.54 ± 0.01	0.08-0.12	0.7-3.15	0.74-3.20

Lowest level ever achieved in NaI(Tl) crystals

Results from SABRE crystals characterization in comparison with other NaI-based experiments.

SABRE PoP: Comparison with other NaI(Tl)-based experiments



Coarasa, I. et al., *Eur. Phys. J. C*, 79:233, 2019.
Adhikari P. et al., *Eur. Phys. J. C* 78:490, 2018.
Bernabei R. et al., *Nuclear Instruments and Methods in Physics Research A*, 592:297– 315, 2008.
Bernabei R. et al., *Nucl. Phys. Atom. Energy*, 19:307-325, 2018.

With only 1 month of data taking !

Background level comparable (for the first time) with that of DAMA/LIBRA phase-1

Potassium direct counting with SABRE PoP

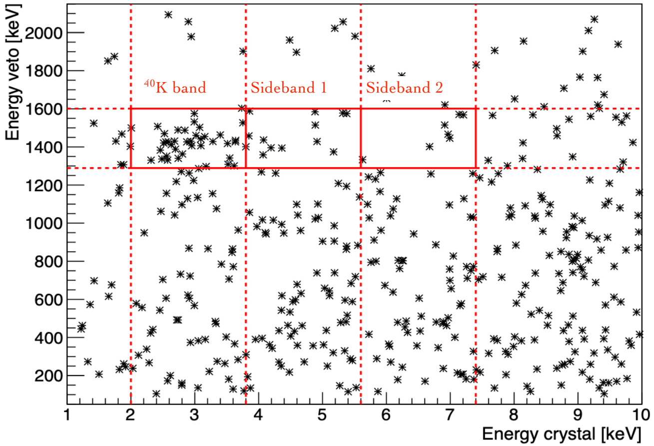
Coincidence analysis between crystal and veto detector

Requirements:

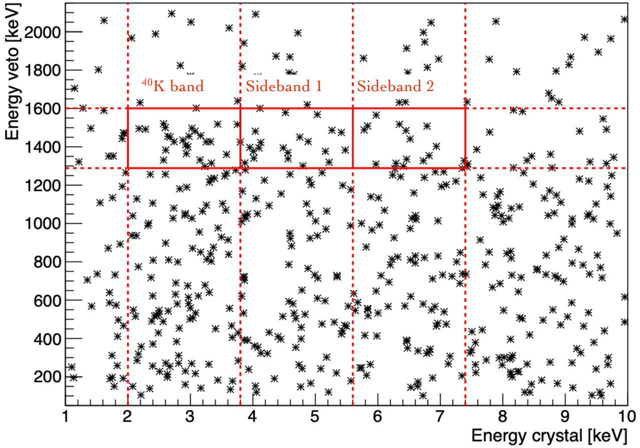
- A crystal energy deposition within $\pm 1\sigma_c$ around the 3.2 keV peak (σ_c energy resolution of the crystal);
- A veto energy deposition within $\pm 2\sigma_v$ around the 1461 keV γ peak (σ_v energy resolution of the veto).

Sidebands used to subtract accidental coincidences.

NaI-31



NaI-33



Efficiency of the selection (calculated by Monte Carlo) taken into account in the analysis.

Exposure: ~60 kg · days

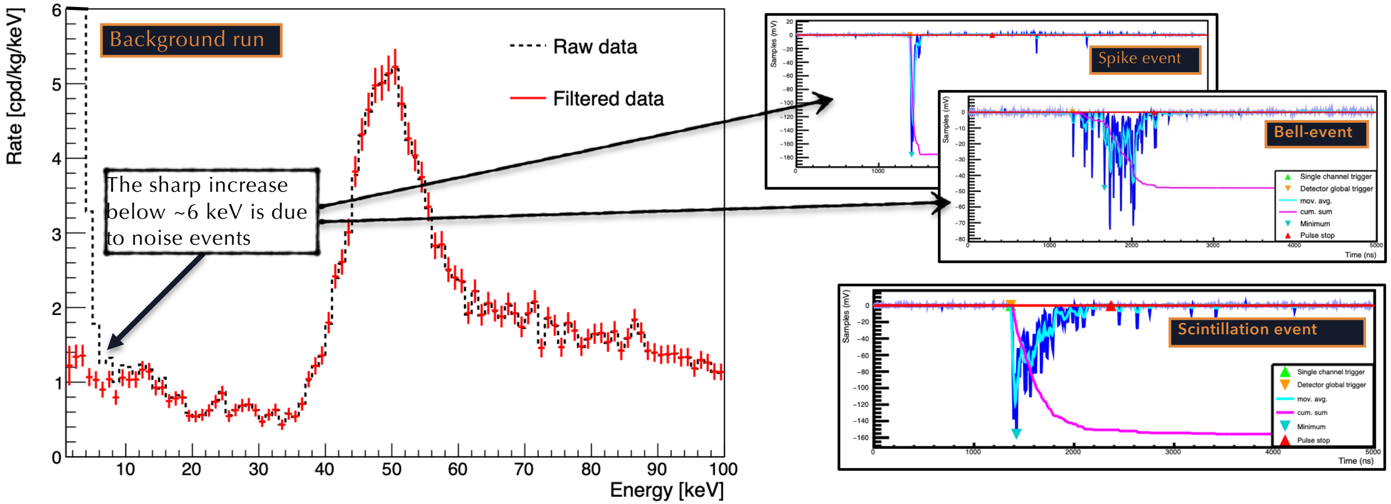
Exposure: ~90 kg · days

	NaI-31	NaI-33
^{40}K activity [mBq/kg]	0.49 ± 0.10	0.07 ± 0.05
^{nat}K contamination [ppb]	15.7 ± 3.2	2.2 ± 1.5
^{nat}K contamination by ICP-MS [ppb]	17.7 ± 1.1	4.6 ± 0.2

Upper limits for NaI-33 (90% CL):

- ^{40}K activity: < 0.15 mBq/kg;
- ^{nat}K contamination: < 4.7 ppb.

NaI-33 low energy data analysis



Pulse Shape Discrimination (PSD) parameters used to select scintillation events

NaI-33 low energy data analysis - PSD parameters

- Amplitude weighted Mean Time:

$$< t >_{600} = \frac{\sum_{t_i<600ns} h_i t_i}{\sum_{t_i<600ns} h_i}$$

time of the i-th sample (starting from the trigger t0)

pulse amplitude in mV

Rejects events that are too long or too short, such as tail-events following very high energy interactions and Cherenkov light emission in PMTs, respectively.

- Charge over Maximum:

$$CoM = \frac{C_{(0,1000)}}{h_{max}}$$

pulse area between 0 and 1000 ns

absolute value of the maximum pulse amplitude in mV

Rejects mainly PMTs noise, such as spike events.

- Head-to-middle pulse shape:

$$C_2/C_1 = \frac{C_{(200,400)}}{C_{(0,200)}}$$

pulse area between 200 and 400 ns

pulse area between 0 and 200 ns

- Middle-to-tail pulse shape:

$$C_3/C_2 = \frac{C_{(400,600)}}{C_{(200,400)}}$$

pulse area between 400 and 600 ns

pulse area between 200 and 400 ns

Reject events that do not have the proper shape of a scintillation pulse, such as bell events.

- Trigger Time Delay: TTD: Time delay between the signals of the two PMTs.

Reject afterglows in PMTs.