Dark matter search with the SABRE experiment

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Dark matter via annual modulation

- Direct detection principle: dark matter scattering off detector nuclei
- Annual modulation of the count rate is a model independent signature
  - period 1 year
  - maximum of modulation around June 2\textsuperscript{nd}

\[ R \approx S_0 + S_m \cos\left(\frac{2\pi}{1\text{yr}}(t - t_0)\right) \]

Expected rate in an Earth-based detector is modulated: \( S_m/S_0 \sim \mathcal{O}(1\%) \)

**DAMA/LIBRA** experiment at LNGS modulation phase1 + phase2: total exposure 2.17 ton x yr

DAMA background \( \sim 1 \text{ cpd/kg/keV} \)
DAMA modulation 0.0095 cpd/kg/keV
Modulation significance 11.9\(\sigma\) C.L.

arXiv:1805.10486
Sodium-iodide with Active Background REjection

1. Development of ultra-high purity NaI(Tl) crystals
   - High purity NaI powder
   - Clean crystal growth method

2. Low energy threshold
   - High QE Hamamatsu PMTs directly coupled to the crystal

3. Passive shielding + active veto
   - Unprecedented background rejection and sensitivity with a NaI(Tl) experiment

4. Two identical detectors in northern and southern hemispheres
   - Seasonal backgrounds have opposite phase in northern and southern hemispheres
   - Dark matter signal has same phase

Other NaI experiments:
- DAMA @LNGS, Italy
- ANAIS @Canfranc, Spain
- COSINE @Yang Yang, South Korea
- Adelaide University
- Australian National University
- Swinburne University
- University of Melbourne

SABRE North @LNGS, Italy
SABRE South @SUPL, Stawell gold mine, Australia

LLNL
PNNL
Princeton/University

LNGS & GSSI
INFN Roma & Sapienza University
INFN Milano and University of Milano

SABRE North @LNGS, Italy
SABRE South @SUPL, Stawell gold mine, Australia
**ANAIS-112 @ Canfranc (Spain)**
Setup: 9 x 12.5 kg crystals (112.5 kg).

- Alpha Spectra crystals: $^{40}$K and $^{22}$Na peaks and $^{210}$Pb (bulk+surface) and $^3$H continua are the most significant contributions in the very low energy region. Bkg ~ 4 cpd/kg/keV (single hit)
- Outstanding light collection: ~15 phe/keV
- Threshold: 1 keV (trigger), 2 keV (sensitivity)

**COSINE-100 @ YangYang (South Korea)**
Joint collaboration between DM-Ice and KIMS
Setup: 8 crystals (106 kg).
Muon tagging. Gamma (3cm Cu + 20 cm Pb) shield, LS veto (~ 2000 l LAB). Data taking started Sep 2016.

- Alpha Spectra crystals. Bkg 2-4 cpd/kg/keV (single hit)
- Threshold: 2 keV (goal is 1 keV)
- R&D for COSINE-200 powder purification and crystal growth facility @ IBS in Korea (mass production facility for purification under construction)
The SABRE crystal

Ultra pure NaI(Tl) crystals
- Astro Grade powder (Sigma Aldrich)
- Clean growth procedure: collaboration between Princeton and RMD, Boston
- A crystal of 3.6 kg (6 kg before cut) has been produced recently (131 mm length x 98 mm diameter)
- Simulation show that the internal background in the crystal can be as low as $\sim 0.15 \text{ cpd/kg/keV}$ in [2-6] keV
  - dominated by Rb (upper limit)
  - provided that $^{210}\text{Pb}$, $^{3}\text{He}$ and cosmogenics are kept under control.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>100</td>
<td>$\sim 13$</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Rb</td>
<td>n.a.</td>
<td>$&lt; 0.35$</td>
<td>$&lt; 0.2$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>U</td>
<td>$\sim 0.02$</td>
<td>$0.5-7.5 \times 10^{-3}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Th</td>
<td>$\sim 0.02$</td>
<td>$0.7-10 \times 10^{-3}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

(*) 2 kg test crystal grown from Astro Grade powder with same technique
Low energy sensitivity

SABRE aims to be sensitive to the energies in the range between [1-6] keV$_{ee}$

Current Design:

- 2 x Hamamatsu R11065-20 3” PMTs per crystal with High QE: >35% and low contaminations
- Direct PMT-Crystal coupling for maximal light yield
- Custom preamplifiers and super bialkali photocathodes → less afterglow and dark noise

Low-radioactivity copper enclosure now @ PU for the assembly of the detector module
Active veto system

- **A liquid scintillator veto (PC+PPO 3g/l)** surrounding the NaI detector at 4π
- Veto events with E > 100 keV in the liquid scintillator
- Strongly reduce:
  - external backgrounds
  - internal backgrounds that release energy also in the liquid scintillator: $^{40}$K

$^{40}$K (11% BR) decays through electron capture to $^{40}$Ar
- $\gamma$ 1460 keV
- X-rays, Auger electrons 3 keV
Double location

- Twin experiments:
  - LNGS (Italy)
  - SUPL (Australia)
- Different environmental conditions:
  - Seasonal effects with opposite phase
  - Rock composition and radio-purity
  - Independent radon, temperature, pressure/control systems

Hosted in the Stawell Gold Mine, Victoria, Australia
- Construction second half of 2018
- Will host SABRE and other experiments
The SABRE Proof-of-Principle (PoP)

Goals:
• Test active veto performance
• Fully characterise the intrinsic and cosmogenic backgrounds

Layout:
• 1 NaI(Tl) crystal
• Crystal and PMTs will be coupled directly with optical coupling gel and sealed into a highly radio-pure copper enclosure
• Active veto:
  • Cylindrical vessel ($\varnothing \times h$) = (1.3 m x 1.5 m)
  • PC+PPO (3g/l) scintillator (mass $\approx$ 2 ton)
  • 10 Hamamatsu R5912-100 PMTs
• External shielding: combination of lead, polyethylene and water, sealed and filled with nitrogen
Status of the SABRE PoP @ LNGS

Shielding and vessel mounted in Hall C
Status of the SABRE PoP @ LNGS

- Shielding assembled
- Veto tank cleaned, internally covered with Lumirror® and equipped with PMTs
- Crystal and enclosure in Princeton, will be mounted and shipped to LNGS
- Data taking with PoP foreseen in the second half of 2018
Monte Carlo simulation of the background

- GEANT4 based code with detailed geometry implementation
  - **Crystal**
  - **Crystal PMTs**: quartz window + body + feedthrough
  - **Enclosure**: wrapping, copper enclosure and small components inside
  - **Crystal Insertion System (CIS)**: copper tube, steel bar
  - **Veto**: steel vessel + liquid scintillator + 10 veto PMTs
  - **Shielding**: water + polyethylene + steel + lead
K measurement mode

- **Target $^{40}\text{K}$ electron capture** (3 keV Auger $e^{-} + 1.46$ MeV $\gamma$) in the crystal and other processes with large energy deposits in the scintillator
- Coincidences Crystal+Scintillator allow to study other intrinsic BKGs that give an energy release in the scintillator

![Graph](image)

- Largest bkg contribution from $^{22}\text{Na}$ mostly below threshold of 2 keV
- 10 ppb of K can be directly measured at 1 ppb precision in ~2 months

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate KMM [cpd/kg/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Cosmogenic</td>
<td>$1.8 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Veto</td>
<td>$6.2 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Enclosure</td>
<td>$1.3 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Crystal PMTs</td>
<td>$1.1 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>CIS</td>
<td>$7.7 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Crystal (no $^{40}\text{K}$)</td>
<td>$5.1 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.7 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Crystal $^{40}\text{K}$</td>
<td>$1.9 \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>

$E_{\text{VETO}}$: $[1280 < 1640]$ keV  
$E_{\text{CRYSTAL}}$: $[2,4]$ keV  
2 months underground  

arXiv:1806.09344
- Test the **active veto rejection power** of the liquid scintillator system
- **Measure background level** after veto in the crystal

![Graph](image)

**Veto on:** $E_{\text{VETO}} < 100$ keV  
$E_{\text{CRYS}}$ [2,6] keV  
6 months underground

<table>
<thead>
<tr>
<th>Component</th>
<th>Rate, veto OFF [cpd/kg/keV]</th>
<th>Rate, veto ON [cpd/kg/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>$3.5 \cdot 10^{-1}$</td>
<td>$1.5 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>Crystal Cosmogenic</td>
<td>$3.0 \cdot 10^{-1}$</td>
<td>$3.9 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Crystal PMTs</td>
<td>$4.3 \cdot 10^{-2}$</td>
<td>$3.5 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Enclosure</td>
<td>$9.5 \cdot 10^{-3}$</td>
<td>$3.6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Veto</td>
<td>$3.0 \cdot 10^{-2}$</td>
<td>$5.7 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>CIS</td>
<td>$3.7 \cdot 10^{-3}$</td>
<td>$4.6 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Total</td>
<td>$7.4 \cdot 10^{-1}$</td>
<td>$2.2 \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>

- **Veto rejection is ~70%**
- **Total background 0.22 cpd/kg/keV,**  
5 times lower than DAMA background
- Highest contribution from Rb in the crystal, but we used the upper limit contamination
SABRE expected sensitivity

Assumptions:
- 3 years exposure
- 50 kg of NaI(Tl) crystals
- average background 0.22 cpd/kg/keV in [2-6] keV region
- Quenching factor for Na: $0.13 < Q_{Na} < 0.21$, for I: $Q_I = 0.09$

The SABRE full scale can:
- Confirm modulation with amplitude observed by DAMA at 6σ
- Refute it at 5σ
- Exclude spin independent WIMP-nuclear scattering as strong as $10^{-42}$ cm$^2$

arXiv:1806.09340
**SABRE** can perform an independent high sensitivity verification of the DAMA/LIBRA modulation.

**SABRE** features:
- High purity NaI(Tl) crystals
- Low energy sensitivity
- Active background rejection
- Twin detectors

- **Proof of Principle** phase in preparation and expected to run in the second half of 2018
- Background levels evaluated with GEANT4 simulations:
  - 0.027 cpd/kg/keV for KMM (\(^{40}\)K excluded)
  - 0.22 cpd/kg/keV for DMM

Full scale experiment can confirm (reject) annual modulation with amplitude observed by DAMA/LIBRA with 3 years of data at 6 (5) sigma.
Backup slides
Crystal cosmogenic background

Cosmogenic activation assumptions:

- $^{22}\text{Na}$ and $^{126}\text{I}$ measured at LNGS on Astro Grade powder
- $^{24}\text{Na}$ and $^{129}\text{I}$ measured from DAMA collaboration on their crystals
- other isotopes measured from ANAIS collaboration on their crystals

ROI: 2-6 keV

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rate, veto OFF [cpd/kg/keV]</th>
<th>Rate, veto ON [cpd/kg/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cosmogenic</td>
<td></td>
</tr>
<tr>
<td>$^{121}\text{Te}$</td>
<td>$2.6 \times 10^{-1}$</td>
<td>$3.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>$3.6 \times 10^{-2}$</td>
<td>$2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{125}\text{I}$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$1.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{129}\text{I}$</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$3.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{126}\text{I}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{121m}\text{Te}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$7.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{123m}\text{Te}$</td>
<td>$7.6 \times 10^{-5}$</td>
<td>$5.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{127m}\text{Te}$</td>
<td>$5.0 \times 10^{-5}$</td>
<td>$4.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{125m}\text{Te}$</td>
<td>$5.3 \times 10^{-6}$</td>
<td>$5.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{24}\text{Na}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tot Cosmogenic (180 days)</td>
<td>$3.0 \times 10^{-1}$</td>
<td>$3.9 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Veto on: $E_{\text{VETO}} < 100$ keV
6 months underground
SABRE expected modulation

\[ m_D = 10 \text{ GeV}, \sigma_{S1,n} = 2.5 \cdot 10^{-40} \text{ cm}^2 \]