Conceptual design of the COSINUS experiment using cryogenic NaI detectors for direct dark matter search

A. Fuss for the COSinus Collaboration
Outline

Motivation for COSINUS

Detectors, Crystals and Prototypes

Conceptual shielding design
+ Background Simulation
Motivation for COSINUS

- Detectors, Crystals and Prototypes
- Conceptual shielding design
- + Background Simulation
DAMA/LIBRA Results

motion of the Earth causes relative modulation of velocity
→ annual variation in the rate
expected period: 1 year
expected phase: cosine peaking June 2\textsuperscript{nd}

Total exposure: 2.17 tonne years (phase 1 + 2)
Statistics: $> 11.9 \sigma$
Period: $0.9987 \pm 0.0008$ years
Phase: 25\textsuperscript{th} May +/- 5 days
Modulation Amplitude: $0.0096 \pm 0.0011$ cpd/kg/keV
Convincing non-DM explanation $\times$

DAMA/LIBRA Islands in the Dark Matter Landscape

Null results shown as:
90% C.L. upper limits on the spin-independent DM particle-nucleon cross section

DAMA/LIBRA:
3σ allowed parameter space
C. Savage et al., Journal of Cosmology and Astroparticle Physics 2009.04 (Apr. 2009), p. 010

- Inconsistency with null-results reported by most other direct dark matter experiments
- **Question:** target dependency of the cross-section?
- **Idea:** Use same target material with low-temperature detection technology
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COSINUS Detector Design

**NaI Target Crystal**
- Scintillator
- Multi-element target
- Mass: ~ 30 – 200 g
- Hygroscopic

**Carrier Crystal**
- Carries the thermometer (TES)
- Glue/oil as interface and link for phonons

**Light absorber**
- Beaker-shaped HP silicon
- Fully active veto to reject surface backgrounds

**Two-channel readout**
- Discrimination between nuclear recoils and β/γ-events
First measurement of a NaI crystals at cryogenic temperature

- NaI energy threshold is $(8.26 \pm 0.02 \text{ (stat.)}) \text{keV}$
- Carrier events identified by pulse shape

$8.26 \text{ keV}$: energy threshold for NaI

~$0.6 \text{ keVee}$: energy threshold for LD

- $^{241}\text{Am}$-line
- Iodine escape
- $^{40}\text{K}$-line

**MODULATION**
Rate vs. time

**COUNTING**
Signal above background

J Low Temp Phys 193 (2018) no.5-6, 1174-1181
COSINUS R&D

1st PROTOTYPE (2016)

- wafer LD
- NaI
- oil

1st measurement of a NaI as cryogenic calorimeter
linear relation between light output and deposited energy

Nal threshold: 10 keV
3.7% detected in light

G. Angloher et al. JINST 12 P11007 (2017)

2nd PROTOTYPE (2016/17)

- Si beaker LD
- NaI
- epoxy resin

successful test of complete COSINUS detector design
energy resolution at zero energy: 15 eV

Nal threshold: 8.3 keV
13 % detected in light

3rd PROTOTYPE (2017)

- Si beaker LD
- NaI
- silicon oil

changed interface to thin layer of silicon oil
commissioning of: in-house electronics and DAQ from MIB

Nal threshold: 6.5 keV

4th → 12th PROTOTYPE (2017-19)

- SiC CAS
- NaI/Nal(Tl)
- new TES

test of new batch of NaI/Nal(Tl) crystals from SICCAS
test of new TES-concept for the NaI crystal

Work ongoing!

Performance goal: 1 keV
Performance goal: 4 %

Schöffner, K. et al. J Low Temp Phys 193 (2018) no.5-6, 1174-1181

NaI Crystal Production

- Collaboration with I. Dafinei from INFN, Roma 1
- Yong Zhu from SICCAS joined the COSINUS collaboration
- Different batches of crystals tested:
  - NaI / NaI(Tl) grown from SICCAS powder (3 g – 30 g crystals)
  - Two 3-inch NaI crystals grown from Astrograde-powder at SICCAS
  - **Very promising radiopurity (ICP-MS analysis):**
    - 5-9 ppb of K at crystals' nose and 22-35 ppb at the tail
      - comparable or even higher purity than DAMA/LIBRA (~ 13 ppb)
  - NaI(Tl) with different amount of thallium dopant
Outline

Motivation for COSINUS

Detectors, Crystals and Prototypes

Conceptual shielding design
+ Background Simulation
Shielding Structure ➔ Geant4 Simulations

• Initial Idea:
  → **Water tank + inner shielding**
    (made of Pb, Cu, PE)

• Simple **Geant4** geometry implemented:
  concentric cylindrical volumes made of respective materials

• Background estimation with simulation
  → Testing different shielding thicknesses
  → No realistic detector design and arrangement was considered
Background Components
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- Ambient neutrons/gammas (origin: outside setup, mostly rock)
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• "Radiogenic" neutrons/gammas (origin: materials in setup)
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• Ambient neutrons/gammas (origin: outside setup, mostly rock)
• "Radiogenic" neutrons/gammas (origin: materials in setup)
• Cosmogenic neutrons (origin: muon interactions)
Estimating the Size of the Water Tank

Constraints:

1. **Reduce ambient neutron/gamma flux** below the neutron/gamma flux due to unavoidable radioactive contaminations of the inner shielding materials (i.e. below the ‘radiogenic’ flux)

2. **Muons** (and their secondaries) should on average travel far enough through the water to create **enough Cerenkov light to have an efficient veto**
Ambient Neutrons at LNGS through H$_2$O

- Spectrum by H. Wulandari

- Simple simulation only using a ‘box’ made of H$_2$O

Integrated Flux above 500 keV: $\sim 7.9 \cdot 10^{-7}$ n cm$^{-2}$ s$^{-1}$
Flux in energy range 1 - 500 keV: $\sim 6.5 \cdot 10^{-6}$ n cm$^{-2}$ s$^{-1}$

⇒ Ambient neutron background negligible!
No constraint for water tank thickness!
Ambient Gammas

Ambient Gammas through water only:

Without inner shielding $O(10^{-6} \text{ cm}^{-2} \text{ s}^{-1})$ reach the detector volume after 3 m water

Total ambient flux

~0.23 cm$^{-2}$ s$^{-1}$

• e.g.: 3 m water + 8 cm Cu: ambient gamma flux is reduced to

~ $2.2 \cdot 10^{-8}$ cm$^{-2}$ s$^{-1}$
Radiogenic Gammas

Contamination levels assumed for Cu and PE:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Cu Contamination</th>
<th>PE Contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>2 µBq/kg</td>
<td>3800 µBq/kg</td>
</tr>
<tr>
<td>Th-232</td>
<td>23 µBq/kg</td>
<td>140 µBq/kg</td>
</tr>
<tr>
<td>K-40</td>
<td>2 µBq/kg</td>
<td>700 µBq/kg</td>
</tr>
<tr>
<td>Co-60</td>
<td>&lt; 2 µBq/kg</td>
<td>&lt; 100 µBq/kg</td>
</tr>
<tr>
<td>Cs-137</td>
<td>&lt; 2 µBq/kg</td>
<td>60 µBq/kg</td>
</tr>
</tbody>
</table>

C. Alduino et al., JINST 11.07 (2016), P07009

Conclusion of simulation:

The gamma flux reaching the detector volume is about an order of magnitude higher when using PE compared to not using PE as an innermost shield.

3 m of water → reduce the ambient gamma flux to (or below) the level of the intrinsic flux. With a thin Cu shield, the ambient flux is definitely reduced below the intrinsic flux.
Radiogenic Neutrons

• Contamination levels used as input to SOURCES4A(C) code:
  (very radiopure reference materials have been selected)

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{238}$U [mBq/kg]</th>
<th>$^{235}$U [mBq/kg]</th>
<th>$^{232}$Th [mBq/kg]</th>
<th>Reference</th>
<th>Neutron yield [cm$^{-3}$ s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>&lt; 0.02</td>
<td>-</td>
<td>&lt; 0.1</td>
<td>[42]</td>
<td>$3.041 \times 10^{-12}$</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt; 0.01</td>
<td>-</td>
<td>&lt; 0.07</td>
<td>[42]</td>
<td>$1.249 \times 10^{-13}$</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt; 0.065</td>
<td>-</td>
<td>&lt; 0.002</td>
<td>[43]</td>
<td>$6.609 \times 10^{-13}$</td>
</tr>
<tr>
<td>PE</td>
<td>&lt; 3.8</td>
<td>&lt; 0.37</td>
<td>&lt; 0.14</td>
<td>[44]</td>
<td>$9.369 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

• SOURCES4A(C) output (neutron yield + spectrum) is used as input for Geant4 simulation

Conclusion of simulation:
- Avoiding PE as an innermost shield reduces the radiogenic neutron background
- Less material (thin inner shield) leads to less sources for radiogenic neutrons
Cosmogenic Neutrons

1) Muon propagation to LNGS laboratory using **MUSUN simulation**:

Flux on surface of (12x12x13)m volume:

\[
0.07304 \text{ s}^{-1} = 2.3 \cdot 10^6 \text{ a}^{-1}
\]

2) Interface to **Geant4 simulation**:

Conclusion of simulation:
If we avoid PE close to the detectors, we will also omit using Pb to minimize neutron production.
Background budget and goal

• Our preferred optimal shielding design omits using Pb and PE, and solely consists of a water tank of 7 m diameter and height + 8 cm Cu shielding

• Gamma-background can be discriminated via two-channel readout

• Dangerous Background: neutrons

• Goal: background-free experiment, i.e. < 1 count kg\(^{-1}\) yr\(^{-1}\) in signal region
  → No exact count estimation possible with simple simulation setup
  → Estimation yields \(O(1 \text{ count kg}^{-1} \text{ yr}^{-1})\) for cosmogenic neutrons and \(O(10^{-2} \text{ count kg}^{-1} \text{ yr}^{-1})\) for radiogenic neutrons
    → Cosmogenic neutron background is ~ 2 orders higher than radiogenic neutron background without veto
    → need for an active muon veto
Geant4 Simulation – Tracking Cerenkov Light in the Water Tank

Storing the energy, hit positions and hit times of each photon

Cerenkov light cone created when e.g. a cosmic muon traverses the water
Hit Patterns on Tank Walls (Reflective Foil)

- Distinguish: - “**Muon Events**” (= muon (+ secondaries) travelling through water tank)
  - “**Shower Events**” (= only secondary particles travel through water tank)
- Only considering “dangerous” events, in which a neutron reaches the inner shielding
Tagging Efficiencies

Different PMT arrangements were tested, e.g.:

- Tank Bottom
- Tank Wall

**Characteristics** (size, quantum efficiency, collection efficiency, etc.) of Hamamatsu 8-inch PMTs were used.

Very efficient reduction of cosmogenic neutron background possible using 20-30 PMTs!
Conclusion

• COSINUS has access to very radiopure NaI crystals (~ 10 ppb K)

• Operating NaI as a cryogenic detector works and provides particle discrimination via two-channel readout

• Background simulations have been made in order to design a dedicated shielding setup for the experiment, reaching the background goal
  ➢ The preferred optimal solution uses a water tank of 7 m diameter and height in combination with an inner shield solely made of 8 cm Cu
  ➢ The water tank will be used as an active muon veto
Thank you for your attention!
Additional Slides
(Extra Material)
Two Phases: COSINUS $1\pi$ and $2\pi$

**COSINUS $1\pi$: Initial Phase**
- 1st measurement with 10 modules for 100 kg days
- Setup planned for 25 modules for 1000 kg days

**Goal:** confirm or rule out nuclear origin of DAMA signal

**COSINUS $2\pi$**
- Increased target mass, upgraded facility

**Goal:** modulation search

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F. Kahlhöfer, K. Schmidt-Hoberg, K. Schäffner, F. Reindl and S. Wild, JCAP 1805 (2018) no.05, 074