COSINUS - Cryogenic Dark Matter searches with NaI crystals

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www.cosinus.it
Search for Dark Matter

- clear evidence for dark matter on different scales
- observation of dark matter based on gravitational pull only
- undiscovered new particles as a well motivated candidate to explain dark matter
- **direct detection**: search for dark matter via elastic scattering of relic dark matter in the detector
Dark Matter searches by Annual Modulation

- small interaction rate of dark matter expected

- excellent knowledge of background required to identify dark matter signal

- movement of earth in dark matter wind leads to **annual modulation** of dark matter signal

- size of modulation amplitude ~10% (threshold dependent)  
  (http://arxiv.org/abs/1209.3339)
Annual Modulation of Dark Matter Interaction Rate

- DAMA/LIBRA experiment searches for dark matter via annual modulation of signal rate
- operation of radiopure NaI(Tl)-crystals and detection of scintillation light from dark matter scattering
- residual signal shows clear sign for an annual modulation of interaction rate in the energy region of 2-6 keVee

![Graph showing residuals over time with 9.3σ significance](image)
Interpretation of Annual Modulation as Dark Matter

- interpretation of annual modulation as dark matter scattering
  \[ \text{arXiv:0808.3607} \]

- standard astrophysical assumptions for WIMP density and velocity

- preferred mass and cross-section area excluded by other dark matter experiments

\[ m_X \approx 50 \text{ GeV} ; \sigma_{Xn} \approx 7 \cdot 10^{-6} \text{ pb} \]
\[ m_X \approx 6-10 \text{ GeV} ; \sigma_{Xn} \approx 10^{-3} \text{ pb} \]
Annual Modulation - what do we know?

- statistically significant observation of annual modulated rate of events observed through NaI(Tl) scintillation light

- **origin of underlying process is unknown**

- observation is **consistent** with expectation from **dark matter** scattering modulated by annual changes of dark matter relative velocity

- detailed systematic studies cannot explain annual fluctuation by background processes

- **assumptions**: quenched scintillation light, together with standard astrophysical assumption could explain signal modulation via dark matter-nucleus scattering
Measurement of Recoil Energy - Signal Quenching

- amount of scintillation light produced depends on underlying scattering process ("quenching")
- origin of scattering process unknown and size of total deposited energy undetermined
- origin of annual modulation hindered

→ measurement of total energy independent from scattering process
Detection of Dark Matter Scattering

- better understanding of underlying scattering process by scintillation light independent energy measurement
- measurement of energy via phonon / heat channel

Nal based experiments

- DAMA/LIBRA (NaI)
- ANAIS (NaI)
- SABRE (NaI)
- COSINE (NaI)
- KIMS (CsI)
- CRESST-II/III (CaWO₄)
- COSINUS (NaI)
- (Super)CDMS (Ge, Si)
- EDELWEISS (Ge)
- CDEX (Ge)
- CoGeNT (Ge)
- DAMIC (Si)
- Xenon (10-100 kton)
- LUX (LZ) (Xe)
- PandaX (Xe)
- DarkSide (Ar)
The Cosinus Collaboration

about 20 scientists from seven institutions from Germany, Italy and Austria:

i. Max-Planck-Institut für Physik- D-80805 München - Germany
ii. INFN - Sezione di Milano-Bicocca, I-20125 Milano - Italy
iii. Dipartimento di Fisica, Universita di Milano-Bicocca, I-20126 Milano - Italy
iv. Institut fur Hochenergiephysik, Österreichische Akademie der Wissenschaften, A-1050 Wien - Austria
v. Atominstitut, Technische Universität Wien, A-1020 Wien - Austria
vi. INFN - Laboratori Nazionale del Gran Sasso, I-67010 Assergi (AQ) - Italy
vii. Gran Sasso Science Institute, I-67100 L'Aquilla - Italy
The COSINUS Experiment - Detection Principle

- cryogenic operation of NaI-crystal
- simultaneous read-out of
  - phonon channel: particle independent measurement of deposited energy (= nuclear recoil energy)
  - (scintillation) light: different response for signal and background events for background rejection ("quenching")

→ separation between nuclear scattering and β/γ background events
COSINUS - Expected Performance

Black: $\beta/\gamma$-background

- flat 1 c/(keV kg day)
- $^{40}$K: 600 $\mu$Bq/kg

Red: $10 \text{ GeV}/c^2$ WIMP with $2 \times 10^{-4}$ pb (Savage et al.)

Light yield = Light signal / Phonon signal

COSINUS - Expected Performance

- Threshold of 1 keV nuclear recoil
- 4% of deposited energy measured as scintillation light

Simulation of WIMP-events
(100 kg d before cuts)

<table>
<thead>
<tr>
<th>Energy</th>
<th># Events</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 keV</td>
<td>1078</td>
<td>45 %</td>
</tr>
<tr>
<td>2-6 keV</td>
<td>1262</td>
<td>53 %</td>
</tr>
<tr>
<td>&gt; 6 keV</td>
<td>46</td>
<td>2 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2386</td>
<td>100 %</td>
</tr>
</tbody>
</table>
The COSINUS Experiment - Challenges

- NaI is hygroscopic → requires careful handling in glove box
- High contamination with $^{40}$K emission of ~3 keV Auger electron possible
- Small signal amplitude

$$
\Delta T \propto \frac{\Delta Q}{c \cdot m}
$$

$$
c \propto \left(\frac{T}{\Theta_D}\right)^3
$$

$c$: specific heat capacity of the crystal

$\Theta_D$: Debye temperature
First NaI-Prototype and Mounting in Cryostat

Construction and operation of first detector module for cryogenic operation

- NaI phonon detector (undoped)
- Light detector (Silicon on Sapphire + TES)
- CdWO₄ carrier crystal
- Copper housing
- 5 cm of Pb to shield radioactivity from the dilution unit of the cryostat
- Decoupling system to reduce microphonic noise

30x30x20 mm³ (66g)
NaI-crystal - Prototype Performance

→ first successful measurement of NaI crystal as cryogenic detector

hits of the CdWO₄ carrier
Nal-crystal - Prototype Performance

- energy threshold: 10 keV
- 3.7% of energy from γ/β-events deposited in detector is measured as scintillation light

exposure after cuts: 0.46 kg d

→ improvement of detector performance needed
Future Plans

- optimisation of performance
  - improve light yield and lower threshold
- measurement of quenching factors
- new prototypes with improved light yield
  - proof of particle discrimination using neutrons

beaker shape light detector of high purity silicon → improved light detection

about 10 kg d needed to clarify if events originate from nuclear recoils
Summary and Conclusion

- DAMA/LIBRA experiment observes annual modulation of rate based on scintillation measurements from NaI(Tl)

- simultaneous measurement of phonon energy (= total energy) provides additional information on scattering process including $\gamma/\beta$-background rejection

- COSINUS is an R&D project aiming for cryogenic operation of NaI-crystals and measurement of total energy

- COSINUS achieved first successful measurement of NaI-crystal as a cryogenic calorimeter
Additional Material
Typically high contamination with $^{40}$K

$^{19}$K 40 (1.248 $\cdot 10^9$ a)

- $\gamma$: 0.043 MeV, 10.66%
- 1.505 MeV, 0.2%
- $\beta^-$: 1.311 MeV, 89.14%

$^{18}$Ar 40 (stable)

- 1.504 MeV, 10.66%
- 1.461 keV, 10.66%
- 1.022 MeV

$^{20}$Ca 40 (stable)

- 0.483 MeV, 0.001%

3 keV Auger electron emitted together with the 1.46 MeV gamma quantum