Search for rare processes with DAMA/LXe at Gran Sasso

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June 2003
The liquid xenon set-up: the detector

- Inner vessel: OFHC low-radioactivity Copper (Internal volume ≈ 2 l)
- No wave-shifter, no diffuser/reflector, direct light collection by three PMTs with MgF₂ windows and quantum efficiency 18-32% @ 175 nm
- Windows in cultured crystal quartz (transm. > 80% to UV of LXe pure scintillator).

<table>
<thead>
<tr>
<th>Materials</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>nat$^{}$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu vessel</td>
<td>&lt; 16 ppt</td>
<td>&lt; 16 ppt</td>
<td>&lt; 10 ppb</td>
</tr>
<tr>
<td>Cultured crystal quartz</td>
<td>&lt; 16 ppt</td>
<td>&lt; 6 ppb</td>
<td>&lt; 11 ppm</td>
</tr>
</tbody>
</table>
The external vessel and the shield

- External vessel: 316 stainless steel cylinder (~ 100 l) with various feedthroughs and flanges in order to work on PMTs, cold head, sensors, etc.
- Insulation vacuum: ~10^{-3} mbar, filled with Cu bricks

<table>
<thead>
<tr>
<th>Materials</th>
<th>$^{238}$U (ppb)</th>
<th>$^{232}$Th (ppb)</th>
<th>natK (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>&lt; 3</td>
<td>&lt; 10</td>
<td>&lt; 33</td>
</tr>
<tr>
<td>MgF$_2$ window</td>
<td>—</td>
<td>&lt; 10</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Dynodes</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
<th>$^{238}$U (ppb)</th>
<th>$^{232}$Th (ppb)</th>
<th>natK (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu bricks</td>
<td>&lt; 0.5</td>
<td>&lt; 1</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>Boliden Pb</td>
<td>&lt; 8</td>
<td>&lt; 0.03</td>
<td>&lt; 0.06</td>
</tr>
<tr>
<td>Boliden2 Pb</td>
<td>&lt; 3.6</td>
<td>&lt; 0.027</td>
<td>&lt; 0.06</td>
</tr>
<tr>
<td>Polish Pb</td>
<td>&lt; 7.4</td>
<td>&lt; 0.042</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>&lt; 0.3</td>
<td>&lt; 0.7</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>&lt; 0.64</td>
<td>27.2</td>
<td>&lt; 3.3</td>
</tr>
</tbody>
</table>
The vacuum/filling/purification/recovery line

Further on radiopurity

Both Kr-free gases have been deep underground for about 10 years

Alloy St707 used in our getters:

\[ \text{<25 ppb } ^{238}\text{U} \quad \text{<10 ppb } ^{232}\text{Th} \quad \text{<7 ppm } \text{natK} \]

OXISORB not used because of its residual radioactivity:

\[ (298\pm33) \text{ ppb } ^{238}\text{U} \quad (431\pm9) \text{ ppb } ^{232}\text{Th} \quad (24\pm5) \text{ ppm } \text{natK} \]

### Isotopic composition of the Xe enriched in \( ^{136}\text{Xe} \)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{136}\text{Xe} )</td>
<td>68.8%</td>
</tr>
<tr>
<td>( ^{131}\text{Xe} )</td>
<td>2.9%</td>
</tr>
<tr>
<td>( ^{132}\text{Xe} )</td>
<td>8.5%</td>
</tr>
<tr>
<td>( ^{134}\text{Xe} )</td>
<td>17.1%</td>
</tr>
</tbody>
</table>

### Isotopic composition of the Xe enriched in \( ^{129}\text{Xe} \) and original (before the first purification cycle) content of trace contaminants

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>( ^{129}\text{Xe} )</th>
<th>( ^{128}\text{Xe} )</th>
<th>( ^{130}\text{Xe} )</th>
<th>Original</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{129}\text{Xe} )</td>
<td>99.5%</td>
<td>(0.25\pm0.05)%</td>
<td>(0.25\pm0.05)%</td>
<td></td>
</tr>
<tr>
<td>( ^{128}\text{Xe} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^{130}\text{Xe} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^{18}\text{O} )</td>
<td>&lt; 3 ppm</td>
<td>&lt; 3 ppm</td>
<td>&lt; 3 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{17}\text{O} )</td>
<td>&lt; 5 ppm</td>
<td>&lt; 5 ppm</td>
<td>&lt; 5 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{2}\text{H} )</td>
<td>&lt; 2 ppm</td>
<td>&lt; 2 ppm</td>
<td>&lt; 2 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{4}\text{He} )</td>
<td>&lt; 3 ppm</td>
<td>&lt; 3 ppm</td>
<td>&lt; 3 ppm</td>
<td></td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{6}\text{Li} )</td>
<td>&lt; 0.02 ppm</td>
<td>&lt; 0.02 ppm</td>
<td>&lt; 0.02 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{36}\text{Kr} )</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td></td>
</tr>
<tr>
<td>( ^{40}\text{Ar} )</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td>&lt; 1 ppm</td>
<td></td>
</tr>
</tbody>
</table>
Exploiting elastic scattering: limits on recoils investigating the WIMP-\(^{129}\)Xe elastic scattering by means of Pulse Shape Discrimination

- Isothermal, maxwellian WIMP velocity distribution with \(v_0 = 220\) km/s and \(v_{\text{esc}} = 650\) km/s
- Helm SI form factor, Ressell et al. SD form factor
- Parameters at fixed values

PLB436 (1998)379
Dark Matter search:

Limits on WIMP-$^{129}$Xe inelastic scattering

Search for characteristic peak (39.58 keV) in the measured energy spectrum as a result of emission of successive de-excitation $\gamma$ from the excited nuclear states.

$$\sigma_I(v) = \frac{\mu^2}{\pi M_N} \langle N^* | M | N \rangle^2 \sqrt{1 - \frac{v_{thr}^2}{v^2}} = \sigma_{I}^{as} \sqrt{1 - \frac{v_{thr}^2}{v^2}}$$

Neutron calibration

The ratio of the measured amount of light from a recoil nucleus to the amount of light from an electron of the same kinetic energy in a pure liquid Xenon scintillators as the one of DAMA experiment has been measured in 1998 both by using an Americium-Boron neutron source and by detecting scattered neutrons at fixed angles using the 14 MeV ENEA-Frascati neutron generator. In 2000/2001 measurements have been repeated at fixed scattering angles by using the 2.5 MeV ENEA-Frascati neutron generator.

Overall averaged value between 30 and 70 keV recoil energy: $0.46 \pm 0.10$
Search for $\beta\beta$ decay in $^{134}\text{Xe}$ and $^{136}\text{Xe}$:

Analysis of the processes $0\nu\beta\beta(0^+\rightarrow0^+)$ in $^{134}\text{Xe}$ and $^{136}\text{Xe}$ following the model of F. Simkovic et al., hep-ph/0204278:

- backgr estimated excluding the energy regions of $0\nu\beta\beta(0^+\rightarrow0^+)$ decays in $^{134}\text{Xe}$ and $^{136}\text{Xe}$.
- residuals

Total Statistics 8823.54 h

Analysing the single processes:

$^{134}\text{Xe}$ $0\nu\beta\beta(0^+\rightarrow0^+)$: $T_{1/2} > 5.8 \times 10^{22}$ y (90%CL)

$^{136}\text{Xe}$ $0\nu\beta\beta(0^+\rightarrow0^+)$: $T_{1/2} > 1.2 \times 10^{24}$ y (90%CL)
Exclusion plot in the positive sector of plane \(<m_\nu>\) versus \(\eta_N\) obtained from the model of F. Simkovic et al., 68% CL and 90% CL.

Fit on residuals with linear combination of the expected signal from \(0\nu\beta\beta(0^+\rightarrow0^+)\) processes in \(^{134}\text{Xe}\) and \(^{136}\text{Xe}\).

The limit value on \(<m_\nu>\) is comparable with those obtained - depending on the model [1-4] - from the result on the \(0\nu\beta\beta(0^+\rightarrow0^+)\) decay mode of \(^{136}\text{Xe}\) alone, in fact they range from 1.1 and 2.9 eV (90%C.L.).


Other limits (90%CL):

\(^{136}\text{Xe} \ 0\nu M\beta\beta(0^+\rightarrow0^+): \ T_{1/2} > 5.0 \times 10^{23} \text{ y} \)
\(^{136}\text{Xe} \ 2\nu \beta\beta(0^+\rightarrow0^+): \ T_{1/2} > 1.0 \times 10^{22} \text{ y} \)
\(^{136}\text{Xe} \ 2\nu \beta\beta(0^+\rightarrow2^+): \ T_{1/2} > 9.4 \times 10^{21} \text{ y} \)

Without background subtraction
Search for electron decay in the channel:
\[ e^- \rightarrow \nu_e \gamma \]
Search for \( \gamma \) with \( \approx 255 \) keV which could accompany the possible decay of any electron in the LXe scintillator and in its surroundings.

Feynman diagram of the hypothetical CNC electron decays:

\[ e^- \rightarrow \nu_e \gamma \]

Total Statistics 2257.7 kg \cdot day

Energy spectrum
In the inset the fitting curve (dashed line) and excluded peak are also shown.

\[ \tau_{\text{CNC}} > 2.0 \cdot 10^{26} \text{ y } 90\% \text{C.L.} \]
Search for the nuclear level excitation of $^{129}$Xe during CNC processes:

$$^{129}\text{Xe} + e^- \rightarrow ^{129}\text{Xe}^* + \nu_e$$

Total Statistics 823.1 kg·day

PLB465(1999)315

Energy spectrum
In the inset fitting curve and excluded peak for the first excited level of $^{129}$Xe are also shown.

Low energy part of the level schema of $^{129}$Xe

$\tau_{\text{CNC}} > 1.1 \cdot 10^{24} \text{ y } 90\% \text{ C.L.}$
New results on CNC processes:
CNC decay of $^{136}\text{Xe}$ into $^{136}\text{Cs}$

$^{136}\text{Xe} \rightarrow ^{136}\text{Cs} + \text{massless uncharged particle} + \overline{\nu}_e$

Total Statistics 8823.54 h

Energy spectrum
In the inset calculated response functions of the DAMA LXe scintillator for the decays of $^{136}\text{Cs}$

$\tau_{\text{CNC}} > 1.3 \cdot 10^{23} \text{ y} \ 90\% \text{ C.L.}$
Search for the nucleon and di-nucleon decay for $^{129}$Xe: PLB493 (2000) 12

Search for the radioactive daughter nuclei ($^{127}$Te, $^{128}$I, $^{127}$Xe) created after the nucleon or di-nucleon decay disappearance in the parent nuclei

### Processes of $N$ and $NN$ decays in the DAMA/LXe detector

<table>
<thead>
<tr>
<th>Initial nucleus</th>
<th>Decay</th>
<th>Daughter nucleus, half-life, modes of decay and energy release (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{129}_{54}$Xe</td>
<td>$n$</td>
<td>$^{128}_{54}$Xe, stable</td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>$^{128}<em>{53}$I, $T</em>{1/2} = 24.99$ m, $\beta^-$ 94% ($Q = 2.127$); $\beta^+$, EC 6% ($Q = 1.258$)</td>
</tr>
<tr>
<td></td>
<td>$nn$</td>
<td>$^{127}<em>{54}$Xe, $T</em>{1/2} = 36.41$ d, EC ($Q = 0.664$)</td>
</tr>
<tr>
<td></td>
<td>$pn$</td>
<td>$^{127}_{53}$I, stable</td>
</tr>
<tr>
<td></td>
<td>$pp$</td>
<td>$^{127}<em>{52}$Te, $T</em>{1/2} = 9.4$ h, $\beta^-$ ($Q = 0.694$)</td>
</tr>
</tbody>
</table>

### Calculated response functions of the DAMA LXe scintillator for the decays

![Graphs showing response functions for $^{127}_{54}$Xe, $^{127}_{52}$Te, and $^{127}_{53}$I in the DAMA/LXe detector.](image-url)
Results for N and NN decay for $^{129}$Xe:

- $\tau_p \rightarrow \text{inv. chn.} > 1.9 \times 10^{24}$ yr 90% C.L.
- $\tau_{pp} \rightarrow \text{inv. chn.} > 5.5 \times 10^{23}$ yr 90% C.L.
- $\tau_{nn} \rightarrow \text{inv. chn.} > 1.2 \times 10^{25}$ yr 90% C.L.

The values are the same or better than those previously established by the Frejius coll. by using 700 t. The limits for the NN decay into $\nu_\tau \nu_\tau$ are set for the first time.

Energy distribution

The dotted line is the 90% C.L. excluded distribution for $^{127}$Te decay ($\tau_{pp}=5.5 \times 10^{23}$ yr); the dashed line is the exclusion for $^{128}$I decay ($\tau_p=1.9 \times 10^{24}$ yr). In the inset the 150--320 keV energy region is shown in linear scale together with the fitting curve (dotted line) and the excluded distribution for the $^{127}$Xe decay ($\tau_{nn}=1.2 \times 10^{25}$ yr).
New results on nucleon and di-nucleon decay for $^{136}$Xe:

Search for the radioactive daughter nuclei ($^{134}$Te, $^{134}$I, $^{135}$I, $^{135}$Xe) created after nucleon or di-nucleon decay or disappearance in the parent nuclei.

Total Statistics 2257.7 kg·day

Results for N and NN decay for $^{136}$Xe (90% C.L.): (most conservative)

$\tau_n > 3.3 \times 10^{23}$ yr, $\tau_p > 4.5 \times 10^{23}$ yr,

$\tau_{np} > 4.0 \times 10^{22}$ yr, $\tau_{pp} > 2.1 \times 10^{23}$ yr

(bckg sub)

Calculated response functions for the decays of:

$^{134}$Te (from $pp$ disappearance),
$^{134}$I (from $np$ disappearance),
$^{135}$I (from $p$ disappearance),
$^{135}$Xe (from $n$ disappearance)
Conclusions

DAMA/LXe operative since long time in different configurations, competitive results obtained on:

- Dark Matter searches
- search for DBD processes in $^{136}$Xe and $^{134}$Xe
- charge-non-conserving processes
- nucleon and di-nucleon decay into invisible channels

Further data taking foreseen

From the former Xelidon expt in 80’s on LXe detectors R&D to the DAMA proposal and first funding on 1990 (by R. Bernabei, P.Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prosperi)

Low background set-up deeply upgraded in fall 1995 and in summer 2000