Results and perspectives in $\beta\beta$ decay experiments by the DAMA-Kyiv Collaboration with HPGe
DAMA: an observatory for rare processes @LNGS
Collaboration

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+ by-products and small scale experiments (MoU): INR-Kyiv

+ in some studies on $\beta\beta$ decays
(DST-MAE projects, inter-univ. Agreeem.): IIT Ropar/Kharagpur, India

+ in some activites collaborators from

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- Moscow Joint Institute for Nuclear Research, Dubna;
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- Nikolaev Inst. of Inorganic Chemistry, Novosibirsk;
- Institute of Theoretical and Experimental Physics, Moscow

**Australia**
- Department of Applied Physics, Curtin University, Perth

**Finland**
- Dept. of Physics, University of Jyvaskyla, Jyvaskyla
Summary of searches for $\beta\beta$ decay modes in various isotopes (partial list)

- Many competitive limits obtained on lifetime of $2\beta^+$, $\epsilon\beta^+$ and $2\epsilon$ processes
  - $(^{40}\text{Ca}, ^{64}\text{Zn}, ^{96}\text{Ru}, ^{106}\text{Cd}, ^{108}\text{Cd}, ^{130}\text{Ba}, ^{136}\text{Ce}, ^{138}\text{Ce}, ^{180}\text{W}, ^{190}\text{Pt}, ^{184}\text{Os}, ^{156}\text{Dy}, ^{158}\text{Dy}, ...)$.

- First searches for resonant $2\epsilon0\nu$ decays in some isotopes

**ARMONIA:** New observation of $2\nu2\beta^- ^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$ (g.s.$\rightarrow 0_1^+$) decay
  - NPA846 (2010)143

**AURORA:** New observation of $2\nu2\beta^- ^{116}\text{Cd}$ decay

**DAMA**

- Previous limits
- DAMA observed 90% C.L.
DAMA/Ge and LNGS STELLA facility

Ge detectors used by DAMA in previous searches:

DAMA/Ge (GeBer)
- 244 cm³ n-type HPGe detector
- Thin Carbon window: 0.76 mm thickness

GeCris
- 465 cm³ p-type HPGe detector
- Thin Cu window: 1 mm thickness

GeMulti
- Four 225 cm³ p-type HPGe detectors mounted in one cryostat with a well in the center
- Thin Al window: 1.3 mm thickness

GeBEGe
- Broad Energy Ge detector (especially designed for low energy γ spectrometry)
- Thin Cu window: 1.5 mm thickness

DAMA results
- Search for ββ decays of many candidate isotopes (next slide)
- Search for ⁷Li solar axions (NPA806(2008)388, PLB711(2012)41)
- First observation of α decay of ¹⁹⁰Pt to the first excited level of ¹⁸⁶Os (PRC83(2011)034603)

Typical shield from environmental radioactivity
- 5-10 cm of OFHC copper
- 5 cm of low activity lead (< 3 Bq/kg of ²¹⁰Pb)
- 15-25 cm of lead
- 10 cm of borated polyethylene (GeBer)
- Air-tight PMMA box flushed with HP nitrogen
First or improved results for $2\beta$ decays of many isotopes

$^{136}\text{Ce}$ $Q_{\beta\beta}=2378.55$ keV; $2\varepsilon$, $\varepsilon\beta^+$, $2\beta^+$; $^{138}\text{Ce}$ $Q_{\beta\beta}=691$ keV; $2\varepsilon$

- CeO$_2$ sample (627 g) in GeCris detector (2299 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{17}$-$10^{19}$ yr [Eur. Phys. J. A 53 (2017) 172]
- CeO$_2$ sample (732 g) in GeCris detector (1900 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{17}$-$10^{18}$ yr [Nucl. Phys. A 930 (2014) 195]
- CeCl$_3$ crystal (6.9 g) in DAMA/Ge detec. (1280 h) $\Rightarrow$ $T_{1/2}$ limits: $(1\div6)10^{15}$ yr [Nucl. Phys. A 824 (2009) 101]

$^{106}\text{Cd}$ $Q_{\beta\beta}=2775.39$ keV; $2\varepsilon$ (res 0$\nu$), $\varepsilon\beta^+$, $2\beta^+$

- $^{106}\text{CdWO}_4$ crystal scintillator (216 g) in GeMulti (13085 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{20}$-$10^{21}$ yr [Phys. Rev. C 93 (2016) 045502]

$^{96}\text{Ru}$ $Q_{\beta\beta}=2714.51$ keV; $2\varepsilon$ (res 0$\nu$), $\varepsilon\beta^+$, $2\beta^+$; $^{104}\text{Ru}$ $Q_{\beta\beta}=1301.2$ keV; $2\beta^-$

- Purified Ru samples in GeMulti det. (0.56kg$\times$yr) $\Rightarrow$ $T_{1/2}$ limits: $10^{20}$-$10^{21}$ yr [Phys. Rev. C 87 (2013) 034607]
- Ru sample (473 g) in GeCrys detector (158 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{18}$-$10^{19}$ yr [Eur. Phys. J. A 42 (2009) 171]

$^{184}\text{Os}$ $Q_{\beta\beta}=1453.7$ keV; $2\varepsilon$ (res 0$\nu$), $\varepsilon\beta^+$; $^{192}\text{Os}$ $Q_{\beta\beta}=412.4$ keV; $2\beta^-$

- Os sample (173 g) in GeCris detector (2741 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{16}$-$10^{17}$ yr for $^{184}\text{Os}$ and $10^{19}$ yr for $^{192}\text{Os}$ [Eur. Phys. J. A 49 (2013) 24]

$^{190}\text{Pt}$ $Q_{\beta\beta}=1383$ keV; $2\varepsilon$ (res 0$\nu$), $\varepsilon\beta^+$; $^{198}\text{Pt}$ $Q_{\beta\beta}=1049$ keV; $2\beta^-$

- Pt sample (42.5 g) in GeCris detector (1815 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{14}$-$10^{16}$ yr for $^{190}\text{Pt}$ and $10^{18}$ yr for $^{198}\text{Pt}$ [Eur. Phys. J. A 47 (2011) 91]

$^{156}\text{Dy}$ $Q_{\beta\beta}=2005.95$ keV; $2\varepsilon$, $\varepsilon\beta^+$; $^{158}\text{Dy}$ $Q_{\beta\beta}=282.7$ keV; $2\varepsilon$

- Dy$_2$O$_3$ sample (322 g) in DAMA/Ge det. (2512 h) $\Rightarrow$ $T_{1/2}$ limits: $10^{14}$-$10^{16}$ yr [Nucl. Phys. A 859 (2011) 126]

$^{100}\text{Mo}$ $Q_{\beta\beta}=3035$ keV; $2\beta^-$

- $^{100}\text{MoO}_3$ sample (1199 g) enriched in $^{100}\text{Mo}$ at 99.5% in GeMulti detector
  $\Rightarrow$ observation of $^{100}\text{Mo}  \rightarrow^{100}\text{Ru}(0^+)$ decay: $T_{1/2} = 6.9^{+1.0}_{-0.8}(\text{stat}) \pm 0.7(\text{syst}) \times 10^{20}$ yr [Nucl. Phys. A 846 (2010) 143]

The best experimental sensitivities in the field for $2\beta$ decays with positron emission
In addition to the transition to the g.s., the $2\beta 2\nu$ decay of $^{100}$Mo was registered also for the transition to the first excited $0^+_{1}$ level of $^{100}$Ru.

If $0^+_{1}$ excited level of $^{100}$Ru ($E=1130$ keV) populated, two $\gamma$ quanta ($591$ keV + $540$ keV) emitted in cascade.

$^{100}$MoO$_3$ sample (mass =1199 g) enriched in $^{100}$Mo at 99.5% installed in GeMulti setup.

### Table: $T_{1/2}$ measured in several experiments:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$T_{1/2}$, $10^{20}$ yr</th>
<th>Year [Ref.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frejus UL (4800 m w.c.), HP Ge 100 cm$^3$, 994 g of $^{100}$Mo (99.5%), 2298 h, only 1-d spectrum;</td>
<td>$&gt; 12$</td>
<td>1992 [19]</td>
</tr>
<tr>
<td>Shudan mine (2090 m w.c.), HP Ge 114 cm$^3$, 956 g of $^{100}$Mo (98.5%), 9970 h, 1-d spectrum;</td>
<td>$6.1^{+1.8}_{-1.1}$</td>
<td>1995 [11]a</td>
</tr>
<tr>
<td>Modane UL (4800 m w.c.), 4 HP Ge detectors (100, 120, 380, 400 cm$^3$), 17 different $^{100}$Mo samples (107–1005 g, 95.1–99.3%, 142–1599 h), sum of 1-d spectra;</td>
<td>$9.3^{+2.8}_{-1.7}$</td>
<td>1999 [14]</td>
</tr>
<tr>
<td>Modane UL (4800 m w.c.), NEMO-3 detector, 6914 g of $^{100}$Mo foils in 12 sectors (95.1–98.9%), 8024 h, individual energies of $\gamma$ and $e^-$, tracks for $e^-$;</td>
<td>$5.7^{+1.5}_{-1.2}$</td>
<td>2007 [15]</td>
</tr>
<tr>
<td>Ground level (10 m w.c.), 2 HP Ge detectors (300 cm$^3$) in coincidence, 1050 g of $^{100}$Mo (98.4%), 21720 h, coincidence spectrum;</td>
<td>$5.5^{+1.2}_{-0.9}$</td>
<td>2009 [16]b</td>
</tr>
<tr>
<td>Gran Sasso UL (3600 m w.c.), 4 HP Ge detectors (225 cm$^3$ each) in coincidence, 1199 g of $^{100}$MoO$_3$ (99.5%), 18120 h, coincidence and 1-d spectra;</td>
<td>$6.9^{+1.2}_{-1.1}$</td>
<td>This work</td>
</tr>
</tbody>
</table>

Aim of the experiment: remeasurement of the Mo sample used before in the Frejus exp. (not in agreement with other results)
1-dimensional energy spectrum analysis

Both peaks at 540 keV and 591 keV expected for \(2\beta2\nu\) decay \(^{100}\text{Mo} \rightarrow ^{100}\text{Ru}(0_{1}^{+})\) are observed in the data collected with \(^{100}\text{MoO}_{3}\).

In the background spectrum they are absent.

Fit of peak @ 539.5 keV: \(E=539.4\pm0.2\) keV; \(S_{540}=319\pm56\) events

Fit of peak @ 590.8 keV: \(E=590.9\pm0.2\) keV; \(S_{591}=278\pm53\) events

\[T_{1/2} = 6.9^{+1.0}_{-0.8} \text{(stat.)} \pm 0.7 \text{(syst.)} \times 10^{20} \text{ yr.}\]

Most of systematic unc. due to calculation of the efficiencies

2-dimensional energy spectrum analysis

Double coincidences when fixing the energy of one of the Ge detectors.

Eight events detected (red)

\[T_{1/2} = 6.8^{+3.7}_{-1.8} \text{(stat.)} \times 10^{20} \text{ yr}\]

in agreement with the half life derived in 1-d analysis
Search for $\beta\beta$ decay in $^{106}$Cd with $^{106}$CdWO$_4$ scintillator in coincidence with 4 HPGe (GeMulti)

$^{106}$Cd, a promising isotope:

- One of the six isotopes candidate for $2\beta^+$ decay
- $\delta = (1.25\pm0.06)\% \Rightarrow$ possible enrichment up to 100%
- $Q_{2\beta} = (2775.39\pm0.10)$ keV $\Rightarrow 2\beta^+, \epsilon\beta^+, 2\epsilon$ modes possible
- Possible resonant $2\epsilon0\nu$ captures to excited level of $^{106}$Pd
- Theoretical $T_{1/2}$ favorable for some $2\nu$ modes ($10^{20} - 10^{22}$ yr)

$^{106}$CdWO$_4$ crystal scintillator:

- Mass: 216 g, 66.4\% enrichment in $^{106}$Cd
- Good scintillation properties
- Active source approach (high detection efficiency)
- Low levels of internal contamination in (U, Th K)
- $\alpha/\beta$ discrimination capability

PbWO$_4$ light-guide ($\varnothing 40 \times 83$ mm)

Reduce PMT background (archaeol. lead: $A(^{210}\text{Pb})<0.3$ mBq/kg)
106\textsuperscript{Cd}WO\textsubscript{4} crystal scintillator in GeMulti: Results

1. In anticoincidence with the HPGe detectors (AC)
2. In coincidence with \(E_{\text{HPGe}} > 200\) keV (CC >200)
3. In coincidence with \(E_{\text{HPGe}} = 511\) keV (CC 511)
4. In coincidence with \(E_{\text{HPGe}} = 1160\) keV (CC 1160)

Energy spectrum of 106\textsuperscript{Cd}WO\textsubscript{4} detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2\(\beta\) decay of 106\textsuperscript{Cd} excluded at 90% CL

- New limits on 2\(\epsilon\), \(\epsilon\beta^+\), 2\(\beta^+\) processes on the level of \(T_{1/2} > 10^{20} - 10^{21}\) yr
- The half-life limit on the \(\epsilon\beta^+2\nu\) decay, \(T_{1/2} > 1.1 \times 10^{21}\) yr, reached the region of theoretical predictions
- For 2\(\epsilon0\nu\) resonant captures: \(T_{1/2} > (8.5 \times 10^{20} - 1.4 \times 10^{21})\) yr
New $^{106}\text{CdWO}_4$ experiment in DAMA/Crys set-up

1) New experiment with $^{106}\text{CdWO}_4$ in (anti)coincidence with two large CdWO$_4$ scintillators mounted in DAMA/Crys set-up @ LNGS

2) High efficiency

3) Experiment in data taking since May 2016
New limits on $2\beta^+$ decay of $^{136}$Ce and $^{138}$Ce with deeply purified cerium sample

Ce purification performed by the liquid-liquid extraction method

- thorium concentration reduced by a factor $\approx 60$
- improved $2\beta$ sensitivity $\approx$ one order of magnitude

The sample of deeply purified CeO$_2$ (627 g) was placed on the endcap of GeCris detector ($T=2299$ h)

No peculiarities in CeO$_2$ spectrum can be ascribed to $2\beta$ decay of $^{136}$Ce or $^{138}$Ce

$\Rightarrow$ New improved half-life limits: $T_{1/2} > 10^{17}$–$10^{19}$ yr

**NB:**

Cerium purification is also motivated in the light of radiopure crystal scintillators development; In fact, Ce is used

- to develop Ce-containing crystal scintillators (e.g., CeF$_3$, CeCl$_3$)
- as a dopant in inorganic scintillators as Gd$_2$SiO$_5$(Ce), YAlO$_3$(Ce), LaBr$_3$(Ce)

**Table:**

<table>
<thead>
<tr>
<th>Chain Nuclide</th>
<th>Activity (mBq kg$^{-1}$) before purification</th>
<th>after 1st purification</th>
<th>after 2nd purification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>77 (28)</td>
<td>$\leq 9$</td>
<td>$\leq 4$</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>$\leq 3$</td>
<td>$\leq 2$</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$^{138}$La</td>
<td>$\leq 0.7$</td>
<td>$\leq 0.6$</td>
<td>$\leq 0.2$</td>
</tr>
<tr>
<td>$^{139}$Ce</td>
<td>$6 \pm 1$</td>
<td>$1.4 \pm 0.3$</td>
<td></td>
</tr>
<tr>
<td>$^{152}$Eu</td>
<td>$\leq 0.5$</td>
<td>$\leq 0.2$</td>
<td></td>
</tr>
<tr>
<td>$^{154}$Eu</td>
<td>$\leq 0.9$</td>
<td>$\leq 0.08$</td>
<td></td>
</tr>
<tr>
<td>$^{176}$Lu</td>
<td>$\leq 0.5$</td>
<td>$0.4 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$850 \pm 50$</td>
<td>$53 \pm 3$</td>
<td>$30.4 \pm 0.7$</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>$620 \pm 30$</td>
<td>$573 \pm 17$</td>
<td>$9.8 \pm 0.5$</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$38 \pm 10$</td>
<td>$\leq 1.8$</td>
<td>$\leq 0.4$</td>
</tr>
<tr>
<td>$^{231}$Pa</td>
<td>$\leq 24$</td>
<td>$\leq 0.4$</td>
<td></td>
</tr>
<tr>
<td>$^{227}$Ac</td>
<td>$\leq 3$</td>
<td>$\leq 1.4$</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$\leq 870$</td>
<td>$\leq 40$</td>
<td>$\leq 12$</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>$11 \pm 3$</td>
<td>$\leq 1.5$</td>
<td>$\leq 0.3$</td>
</tr>
</tbody>
</table>
Running and future experiments

- Experiment running since February 2015 with deeply purified Nd$_2$O$_3$ sample (2381 g) in GeMulti detector to investigate 2$\beta$ decay of $^{150}$Nd to excited levels of $^{150}$Sm:
  - Background rate in the region of expected peaks (334.0 keV and 406.5 keV) ≈ 2 counts/keV/d
  - Expected $T_{1/2}$ sensitivity after 500 days of measurements: $1.3 \times 10^{20}$ yr (90%CL)

- New experiment to search for 2$\beta$ of osmium (and $\alpha$ decay of osmium to excited level of daughter nuclei) in progress with BEGe detector:
  - Detection efficiency significantly improved by cutting the osmium roads into thin (0.8-1 mm) plates and by using the BEGe detector

- Purification of Er, Yb, and Sm is in progress for experiments to search for resonant 2$\varepsilon$0$\nu$ processes in these nuclei
Conclusions

Many and competitive results have been obtained by the DAMA-Kyiv collab. in the search for $\beta\beta$ decays with HPGe detectors @ the STELLA facility of LNGS:

- First or improved limits on the half-lives of double beta decays of $^{96}$Ru, $^{104}$Ru, $^{106}$Cd, $^{112}$Sn, $^{124}$Sn, $^{136}$Ce, $^{138}$Ce, $^{156}$Dy, $^{158}$Dy, $^{184}$Os, $^{192}$Os, $^{190}$Pt and $^{198}$Pt

- The best experimental sensitivities in the field for $2\beta$ decays with positron emission (useful to distinguish the mechanism of neutrinoless $2\beta$ decay)

- Possible resonant $2\epsilon0\nu$ processes investigated in several candidate isotopes

- New observation of the $2\beta2\nu$ decay of $^{100}$Mo to the first excited $0^+_{1}$ level of $^{100}$Ru with the coincidence technique in the ARMONIA experiment

- New and competitive limits on $2\epsilon$, $\epsilon\beta^+$, $2\beta^+$ processes of $^{106}$Cd with a $^{106}$CdWO$_4$ detector in coincidence with 4 HPGe detectors ($T_{1/2} > 10^{20}$-$10^{21}$ yr, reached the region of theoretical predictions for the $\epsilon\beta^+2\nu$ decay)