Risultati recenti e prospettive sullo studio del doppio decadimento beta con cristalli scintillatoti (DAMA set-up)

103º Congresso Nazionale della Società Italiana di Fisica
Trento, 11-15 Settembre 2017
DAMA Experimental Activities

DAMA Collaboration (spokesperson: prof. R. Bernabei):
Roma2, Roma1, LNGS-INFN, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati e ENEA-Casaccia
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur/Ropar, India

DAMA: an observatory for rare processes @LNGS

http://people.roma2.infn.it/dama
Strengths of $\beta\beta$ experiments by ULB crystal scintillators

- Well known technology
- High duty cycle
- Large mass possible
- Enrichment possible in many cases
- "Ecological clean" set-up; no safety problems
- Cheaper than other considered technique
- Relatively small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- Possibility of high light response in many cases
- Effective routine calibrations feasible in the same conditions as production runs
- Absence of microphonic noise
- Possibility of application both in passive and active source approaches as well as with coincidence/anticoincidence techniques
- Many isotopes and decay modes explorable
- Etc.
Esempi di isotopi utili per l’investigazione di modi di decadimento doppio beta impiegando cristalli scintillatori con la tecnica della sorgente attiva

<table>
<thead>
<tr>
<th>Isotops</th>
<th>Nat. Ab. (%)</th>
<th>Q (keV)</th>
<th>Decay Mode</th>
<th>Scintillator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{64}$Zn</td>
<td>8.63</td>
<td>1095.7</td>
<td>εβ⁺, 2ε</td>
<td>ZnWO₄, CdWO₄</td>
</tr>
<tr>
<td>$^{70}$Zn</td>
<td>0.62</td>
<td>998.5</td>
<td>2β⁻</td>
<td>ZnWO₄, CdWO₄</td>
</tr>
<tr>
<td>$^{180}$W</td>
<td>0.12</td>
<td>144</td>
<td>2ε</td>
<td>ZnWO₄, CdWO₄, PbWO₄</td>
</tr>
<tr>
<td>$^{186}$W</td>
<td>28.43</td>
<td>489.9</td>
<td>2β⁻</td>
<td>ZnWO₄, CdWO₄, PbWO₄</td>
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<tr>
<td>$^{106}$Cd</td>
<td>1.25</td>
<td>2771</td>
<td>2β⁺, εβ⁺, 2ε</td>
<td>ZnWO₄, CdWO₄, PbWO₄</td>
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<tr>
<td>$^{106}$W</td>
<td>0.89</td>
<td>269</td>
<td>2ε</td>
<td>CdWO₄</td>
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<tr>
<td>$^{106}$Cd</td>
<td>28.73</td>
<td>536.8</td>
<td>2β⁻</td>
<td>CdWO₄</td>
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<tr>
<td>$^{116}$Cd</td>
<td>7.49</td>
<td>2805</td>
<td>2β⁻</td>
<td>CdWO₄</td>
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<tr>
<td>$^{40}$Ca</td>
<td>96.941</td>
<td>193.78</td>
<td>2ε</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<td>$^{40}$Ca</td>
<td>0.004</td>
<td>990.4</td>
<td>2β⁻</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<tr>
<td>$^{48}$Ca</td>
<td>0.187</td>
<td>4272</td>
<td>2β⁻</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<tr>
<td>$^{136}$Ce</td>
<td>0.185</td>
<td>2419</td>
<td>2β⁺, εβ⁺</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<tr>
<td>$^{138}$Ce</td>
<td>0.251</td>
<td>693</td>
<td>2ε</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<tr>
<td>$^{142}$Ce</td>
<td>11.114</td>
<td>1416.9</td>
<td>2β⁻</td>
<td>CeCl₃, CeF₃, CeBr₃</td>
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<tr>
<td>$^{130}$Ba</td>
<td>0.106</td>
<td>2611</td>
<td>2β⁺, εβ⁺, 2ε</td>
<td>PbMoO₄, LiMoO₄, CaMoO₄</td>
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<tr>
<td>$^{92}$Mo</td>
<td>14.84</td>
<td>1649</td>
<td>εβ⁺, 2ε</td>
<td>PbMoO₄, LiMoO₄, CaMoO₄</td>
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<tr>
<td>$^{100}$Mo</td>
<td>9.63</td>
<td>3034</td>
<td>2β⁻</td>
<td>PbMoO₄, LiMoO₄, CaMoO₄</td>
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<tr>
<td>$^{84}$Sr</td>
<td>0.56</td>
<td>1786.8</td>
<td>εβ⁺</td>
<td>SrCl₂, SrI₂(Eu)</td>
</tr>
</tbody>
</table>
DAMA/Ge and LNGS STELLA facility - Some main previous results

- RDs on highly radiopure NaI(Tl) set-up
- several RDs on low background PMTs
- qualification of many materials
- meas. on Li₆Eu(BO₃)₃ (NIMA572(2007)734)
- ββ decay in $^{100}$Mo with the 4π low-bckg HPGe facility of LNGS (NPA846(2010)143)
- search for $^7$Li solar axions (NPA806(2008)388, PLB711(2012)41)
- meas. with a Li₂MoO₄ (NIMA607(2009)573)
- ββ decay of $^{136}$Ce and $^{138}$Ce (NPA824(2009)101)
- First observation of α decay of $^{190}$Pt to the first excited level (137.2 keV) of $^{186}$Os (PRC83(2011)034603)
- ββ decay in $^{190}$Pt and $^{198}$Pt (EPJA47(2011)91)
- ββ decay of $^{156}$Dy, $^{158}$Dy (NPA859(2011)126)
- Contaminations of SrI₂(Eu) (NIMA670(2012)10)
- Radioactive contamination of $^7$LiI(Eu) (NIMA704(2013)40)
- ββ decay of $^{96}$Ru and $^{104}$Ru (EPJA42(2009)171, PRC87(2013)034607)
- First search for rare decays of Os (EPJA49(2013)24)
- Search for double beta decay of $^{136}$Ce and $^{138}$Ce (Nucl.Phys. A930 (2014) 195-208)
- Double beta decay in $^{112}$Sn and $^{124}$Sn (NIMA797 (2015) 130-137)
**DAMA R&D - Some main previous results:**

- Scintillators developments: radio-purification, enrichment, optical features, etc.
- Exploiting the potentiality of the low background scintillation technique to investigate rare processes with high sensitivity
- Realization of pilot experiments

**Pairing materials:**

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{238}$U (ppb)</th>
<th>$^{232}$Th (ppb)</th>
<th>$^{40}$K (ppm)</th>
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<tbody>
<tr>
<td>Cu</td>
<td>&lt; 0.5</td>
<td>&lt; 1</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>Pb bottle</td>
<td>&lt; 8</td>
<td>&lt; 0.03</td>
<td>&lt; 0.06</td>
</tr>
<tr>
<td>Pb bottle 2</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>Polietene</td>
<td>&lt; 0.3</td>
<td>&lt; 0.7</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>&lt; 0.64</td>
<td>&lt; 27.2</td>
<td>&lt; 3.3</td>
</tr>
</tbody>
</table>

**References:**

Summary of searches for $\beta\beta$ decay modes in various isotopes (partial list)

- Many competitive limits obtained on lifetime of $2\beta^+, \varepsilon\beta^+$ and $2\varepsilon$ processes ($^{40}$Ca, $^{64}$Zn, $^{96}$Ru, $^{106}$Cd, $^{108}$Cd, $^{130}$Ba, $^{136}$Ce, $^{138}$Ce, $^{180}$W, $^{190}$Pt, $^{184}$Os, $^{156}$Dy, $^{158}$Dy, ...).
- First searches for resonant $0\nu 2\varepsilon$ decays in some isotopes

- DAMA limits
- DAMA observed
- Previous limits

ARMONIA: New observation of $2\nu 2\beta^- 100$Mo$\rightarrow 100$Ru (g.s.$\rightarrow 0^+)$ decay  
NPA846 (2010)143

AURORA: New observation of $2\nu 2\beta^- 116$Cd decay  
In the following present
STATUS and PERSPECTIVES on:

- ZnWO₄ crystal scintillators to search for 2β in Zn and W isotopes
- ¹⁰⁶CdWO₄/¹¹⁶CdWO₄ crystal scintillators to search for 2β in ¹⁰⁶Cd/¹¹⁶Cd
- Improvement of crystal radio-purity by recrystallization technique
- SrI₂(Eu) crystal scintillator for low-level counting experiments
Development of low background ZnWO₄ crystal scintillators with large volume and high scintillation properties is important to investigate double beta decay modes in Zn and W isotopes with source=detector approach.

- Various detectors with mass 0.1-0.7 kg realized by exploiting different materials and techniques.
- Inside a cavity (filled up with high-pure silicon oil) \( \phi 47 \times 59 \) mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Energy release ((Q_{\beta\beta})) (keV)</th>
<th>Isotopic abundance (%)</th>
<th>Decay channels</th>
<th>Number of mother nuclei in 100 g of ZnWO₄ crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{64}\text{Zn} \rightarrow ^{64}\text{Ni})</td>
<td>1095.7(0.7)</td>
<td>49.17(75)</td>
<td>(2\epsilon, \epsilon\beta^+)</td>
<td>9.45 × 10^{22}</td>
</tr>
<tr>
<td>(^{70}\text{Zn} \rightarrow ^{70}\text{Ge})</td>
<td>998.5(2.2)</td>
<td>0.61(10)</td>
<td>(2\beta^-)</td>
<td>1.17 × 10^{21}</td>
</tr>
<tr>
<td>(^{180}\text{W} \rightarrow ^{180}\text{Hf})</td>
<td>144(4)</td>
<td>0.12(1)</td>
<td>(2\epsilon)</td>
<td>2.31 × 10^{20}</td>
</tr>
<tr>
<td>(^{186}\text{W} \rightarrow ^{186}\text{Os})</td>
<td>489.9(1.4)</td>
<td>28.43(19)</td>
<td>(2\beta^-)</td>
<td>5.47 × 10^{22}</td>
</tr>
</tbody>
</table>

References:
PLB658(2008)193
NPA826(2009)256
NIMA626-627(2011)31
JP38(2011)115107
EPJC73 1(2013) 2276
PS90 8(2015)085301
NIMA833 (2016) 77-81
Final results on the present stage of investigation of $\beta\beta$ decay modes in Zn and W isotopes with low background ZnWO$_4$

**Improved (up to 2 orders of magnitude) $T_{1/2}$ limits on $\beta\beta$ decay modes of $^{64}$Zn, $^{70}$Zn, $^{180}$W and $^{186}$W:**

now at level of $10^{18} - 10^{21}$ yr

$\rightarrow$ up to now only 5 nuclides ($^{40}$Ca, $^{78}$Kr, $^{112}$Sn, $^{120}$Te and $^{106}$Cd) over 34 candidates to $2\varepsilon$, $\varepsilon\beta^+$, $2\beta^+$ processes have been studied at similar level of sensitivity in direct search experiments

1. A possible positive hint of the $(2n+0n)\varepsilon\beta^+$ decay in $^{64}$Zn with $T_{1/2} = (1.1 \pm 0.9) \times 10^{19}$ yr [Bikit et al., Appl. Radiat. Isot. 46(1995)455] excluded
2. the $0\nu2\beta$ capture in $^{180}$W is of particular interest because of possible resonant process;
3. the rare $\alpha$ decay of the $^{180}$W with $T_{1/2} = (1.3^{+0.6}_{-0.5}) \times 10^{18}$ yr observed and new limit on the $T_{1/2}$ of the $\alpha$ transition of the $^{183}$W to the metastable level $1/2^-$ at 375 keV of $^{179}$Hf has been set: $T_{1/2} = 6.7 \times 10^{20}$ yr.

**ZnWO$_4$ - Work in Progress...**

- New 4 crystal scintillators in the DAMA/R&D in data taking:
  - radioactive contamination and scintillation performances
  - study of double beta decay modes in Zn and W isotopes
- Cryostat for low temperature measurement with scintillation, testing in progress
- Detectors realized
- Lowering the energy threshold
- Measurements of anisotropy at low energy with Neutron Generator in progress at Casaccia ENEA lab
- Development of electronics

Total exposure = 0.529 kg x y

**Development of Detectors with Anisotropic Response**
For Dark Matter Search in Directionality Approach are in progress
The used $^{106}\text{CdWO}_4$ crystal scintillator

- Samples of cadmium were purified by vacuum distillation (Institute of Physics and Technology, Kharkiv) and the Cadmium tungstate compounds were synthesized from solutions.
- Crystal boule was grown by the low-thermal-gradient Czochralski technique (NIIC Novosibirsk) (initial powder 265 g).
- Crystal scintillator (216 g mass), 66.4% enrichment in $^{106}\text{Cd}$ ($2.66 \times 10^{23}$ nuclei of $^{106}\text{Cd}$) measured by thermal ionisation mass-spectrometry $\Rightarrow$ 2$^{\text{nd}}$ enriched $\text{CdWO}_4$ crystal ever produced.

1$^{\text{st}}$ exp: single crystal in DAMA/R&D  
2$^{\text{nd}}$ exp: coincidence with 4 HP-Ge

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

The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain in the $^{228}\text{Th}$ sub-chain of the $^{232}\text{Th}$ family in $^{106}\text{CdWO}_4$ crystal:

- $^{224}\text{Ra}$ ($Q = 5.789$ MeV, $T_{1/2} = 3.66$ d)
- $^{220}\text{Rn}$ ($Q = 6.405$ MeV, $T_{1/2} = 55.6$ s)
- $^{216}\text{Po}$ ($Q = 6.906$ MeV, $T_{1/2} = 0.145$ s)

The energy spectra accumulated over 6935 h by the $^{106}\text{CdWO}_4$ detector:

- in anticoincidence with the $^{nat}\text{CdWO}_4$ detectors
- in coincidence with event(s) in at least one of the $^{nat}\text{CdWO}_4$ detectors with energy:
  - $E > 200$ keV
  - $E$ in energy window around 511 keV
  - $E$ in energy window around 1160 keV

|$^{232}\text{Th}$ | $^{232}\text{Th}$ | $<0.07$
|$^{228}\text{Th+subch.}$ | | $<0.02$
|$^{238}\text{U}$ | $^{238}\text{U}$ | $<0.6$
|$^{234}\text{Th}$ | | $<0.6$
|$^{230}\text{Th}$ | | $<0.4$
|$^{210}\text{Po}$ | | $<0.2$
Estimation of sensitivity

Expected signal for $^{106}\text{Cd}$ $0\nu 2\beta^+(0^+ \rightarrow 0^+)$:

Spectrum of $^{106}\text{CdWO}_4$ detector when one of the two CdWO$_4$ detectors detects $\gamma$ of 511 keV ($\pm 2\sigma$)

Spectrum of $^{106}\text{CdWO}_4$ detector when both the CdWO$_4$ detectors detect $\gamma$ of 511 keV ($\pm 2\sigma$)

Sensitivity after 1yr in the hypothesis of about 30 background counts in [0.-3.] MeV:

$0\nu \epsilon\beta^+$ (g.s.): $T_{1/2} \approx 5 \times 10^{21}$ yr

$2\nu 2\beta^+$ (g.s.): $T_{1/2} \approx 2 \times 10^{21}$ yr

In the region of theoretical predictions: $T_{1/2} \approx 10^{20} - 10^{22}$ yr

Note that, up to now, $2\nu$ mode of the $2\beta^+$ processes has not been detected unambiguously: there are only indications for $^{130}\text{Ba}$ and $^{78}\text{Kr}$
The AURORA experiment in the DAMA/R&D set-up:
Investigation of $2\beta$ decay of $^{116}$Cd with enriched $^{116}$CdWO$_4$ crystal scintillators

$^{116}$Cd: one of the best isotope for $0\nu2\beta$ decay search:
- $Q_{\beta\beta} = 2813.44(13)$ keV
- $\delta = 7.49(18)$%
- possible high isotopic enrichment
- promising theoretical calculation

$^{116}$CdWO$_4$ crystal scintillators
Grown by the low-thermal-gradient Czochralski technique after deep purification of $^{116}$Cd and W;
+ annealing to improve the optical transmission curve

✓ Good optical and scintillation properties
✓ $^{116}$CdWO$_4$ crystals enriched at 82%
✓ Active source approach (high detection efficiency)
✓ Low levels of internal contamination in (U, Th, K)
✓ $\alpha/\beta$ discrimination capability

Two enriched $^{116}$CdWO$_4$ crystal scintillators
(total mass: 1.162 kg, $^{116}$Cd @ 82%)
✓ Started in 2011
✓ Upgrade - March 2014
✓ Total live time since 2014: 25037 h
✓ Background level at 2.7-2.9 MeV: 0.1 counts/keV/kg/yr
Radioactive contaminations of $^{116}$CdWO$_4$ crystal scintillators

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity mBq/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>0.61(2)</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>$^{238}$U</td>
<td>0.022(3)</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>0.59(7)</td>
</tr>
<tr>
<td>$^{234}$Th</td>
<td>$^{234}$Th</td>
<td>0.64(7)</td>
</tr>
<tr>
<td>$^{230}$Th</td>
<td>$^{230}$Th</td>
<td>0.11(2)</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>$^{226}$Ra</td>
<td>≤ 0.01</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>$^{210}$Pb</td>
<td>0.6(1)</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$^{40}$K</td>
<td>0.20(1)</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>$^{110m}$Ag</td>
<td>&lt;0.06</td>
</tr>
</tbody>
</table>

Total $\alpha$ activity = 2.27 mBq/kg
**AURORA Experiment: Result for $2\nu 2\beta$ Decay of $^{116}$Cd & $T_{1/2}$ Limit on $0\nu 2\beta$ Decay of $^{116}$Cd**

$$T_{1/2} = [2.69 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.})] \times 10^{19} \text{ yr} \quad \text{(the most accurate value up to date)}$$

**Fit in 2.5–3.2 MeV:** $-3.7 \pm 10.6$ counts

$$T_{1/2} > 2.4 \times 10^{23} \text{ yr} \quad \text{@ 90\% C.L.}$$

**Effective Majorana neutrino mass:**

$$\langle m_\nu \rangle < 1.1 – 1.6 \text{ eV} \quad [1-4]$$

New improved limits on $T_{1/2}$ for $0\nu 2\beta$ decay to excited levels of $^{116}$Sn in the range:

$$(3.6–6.3) \times 10^{22} \text{ yr}$$

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Improvement of radiopurity of $^{116}$CdWO$_4$ by recrystallization

Re-crystallized by the low-thermal-gradient Czochralski technique in a platinum crucible

Crystal n.3 used (326 g mass)

60% of initial mass after recrystallization

Side surface made opaque by grinding paper to improve light collection

Radioactive contamination of the samples (before an after recrystallization) measured in the DAMA/CRYS setup @ LNGS

- $^{228}$Th reduced by a factor ~10 $\Rightarrow$ 0.01 mBq/kg
- $\alpha$ activity reduced by a factor ~3 $\Rightarrow$ 1.6 mBq/kg

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide (sub-chain)</th>
<th>Activity (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before recrystallization</td>
<td>After recrystallization</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>0.13(7)</td>
</tr>
<tr>
<td></td>
<td>$^{228}$Th</td>
<td>0.10(1)</td>
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<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>1.8(2)</td>
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<tr>
<td></td>
<td>$^{226}$Ra</td>
<td>$\leq$0.1</td>
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<tr>
<td></td>
<td>$^{234}$U + $^{230}$Th</td>
<td>0.6(2)</td>
</tr>
<tr>
<td></td>
<td>$^{210}$Po</td>
<td>1.6(2)</td>
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<tr>
<td>Total $\alpha$</td>
<td></td>
<td>4.44(4)</td>
</tr>
</tbody>
</table>

main background component for $^{116}$Cd 0ν2β decay
Feasibility Study for Low-Level Counting Experiment by SrI₂(Eu) Crystal Scintillator

Features in literature
Density: (4.5 – 4.6) g/cm³
Melting point: 515 °C
Index of refraction: 1.85
Wavelength of emission maximum: 429 – 436 nm
Light yield: (68 – 120) photons/keV
Energy resolution (FWHM) for 662 keV γ: (2.6 – 3.7)%
Scintillation decay time at 300 K: (0.6 – 2.4) µs

PSD capability

- A single crystal of SrI₂ doped by 1.2% of Eu was grown in a quartz ampoule using the vertical Stockbarger method
- Studied radioactive contamination and scintillation property
- Applicability of SrI₂(Eu) to the search for ββ decay of ⁸⁴Sr was demonstrated for the first time.
- New improved half-life limits were set on 2ε and εβ⁺ decay in ⁸⁴Sr at level of T½ ∼ 10¹⁵ – 10¹⁶ yr.

Work in Progress....
- Radio-purity improvements
- Studying different crystal growing technique
- Growing large volume SrI₂(Eu) crystal scintillator to study its radioactive contamination and scintillation performances
Conclusions

- Many and competitive results have been obtained in the search for $\beta\beta$ decay by the DAMA experimental set-ups at LNGS
- Continue efforts to develop new/improved crystal scintillators for low bckg physics
- Experiments on $2\beta$ decay of Zn and W isotopes running/under-improvement
- Experiments for development of crystal scintillators with anisotropic response for nuclear recoil in keVee region are in progress
- Experiments on $2\beta$ decay of $^{106}\text{Cd}$ and $^{116}\text{Cd}$ running/under-improvement
- Search for $2\beta$ processes in $^{116}\text{Cd}$ with $^{116}\text{CdWO}_4$ (enriched to 82%) scintillation detectors (1.16 kg) just concluded in the DAMA/R&D set-up:
  - $T_{1/2}(2\nu2\beta) = [2.69 \pm 0.02\text{(stat.)} \pm 0.14\text{(syst.)}] \times 10^{19}\text{ yr}$ (the most accurate value up to date)
  - $T_{1/2}(0\nu2\beta) \geq 2.4 \times 10^{23}\text{ yr} \rightarrow \langle m\nu \rangle < (1.1 - 1.6)\text{ eV}$ (the best limit)
  - Internal $^{228}\text{Th}$ (main bkgd) can be strongly reduced by re-crystallization
- Studies for the Improvement of crystal scintillators’ radiopurity are in progress
- Feasibility Study for Low-Level Counting Experiment by $\text{SrI}_2$(Eu)Crystal Scintillator