Risultato finale dell'esperimento Aurora per lo studio del decadimento 2β del ^{116}Cd mediante un cristallo scintillatore $^{116}CdWO_4$ arricchito in ^{116}Cd

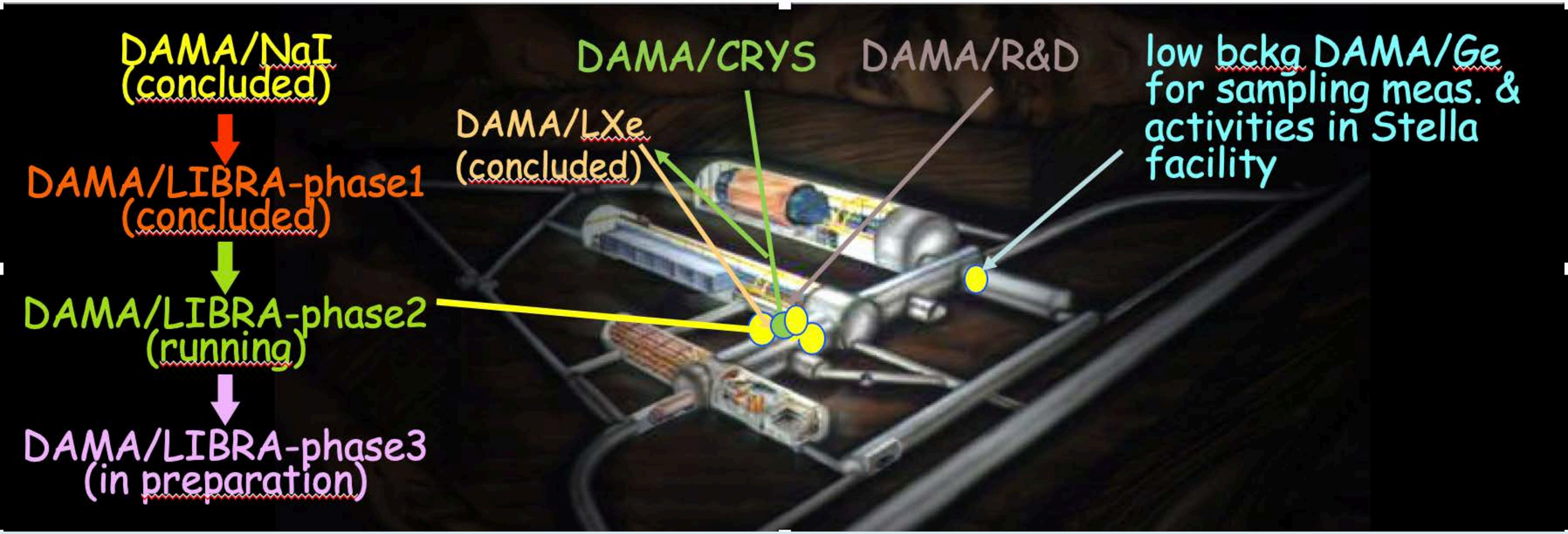
105° Congresso Nazionale SIF

L'Aquila - Gran Sasso Science Institute, 23 - 27 settembre 2019

Dr. Alessandro Di Marco

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev + other institutions

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

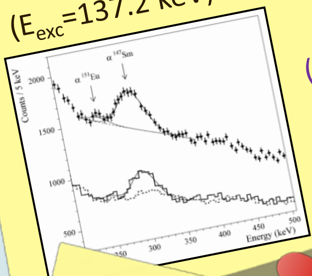
+ in some studies on ββ decays (DST-MAE & Inter-Univ. project): IIT Kharagpur and Ropar, India

web site: http://people.roma2.infn.it/dama

Main results obtained with DAMA set-ups in the search for rare processes

- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt (observed 2ν2β decay in ^{100}Mo, ^{116}Cd)
- The best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os



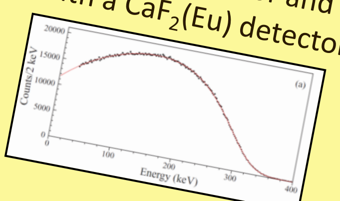
($T_{1/2}=5\times10^{18}$yr)

Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

Search for PEP violating processes in Sodium and in Iodine

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillator and ^{48}Ca with a CaF_2(Eu) detector



Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Dark Matter investigation

… many others are in progress

Decay modes for Double Beta Decay (DBD)

①

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

$(A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu_e$

$(A,Z) + e_a \rightarrow (A,Z-2) + e^+ + 2\nu_e$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + 2\nu_e$

2ν Double Beta Decay (2νββ)
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ yr

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②

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

$(A,Z) \rightarrow (A,Z-2) + 2e^+$

$(A,Z) + e_a \rightarrow (A,Z-2) + e^+$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + \gamma$

neutrinoless Double Beta Decay (0νββ)
never observed except
Klapdor's meas. - $\tau \Rightarrow 10^{25}$ yr

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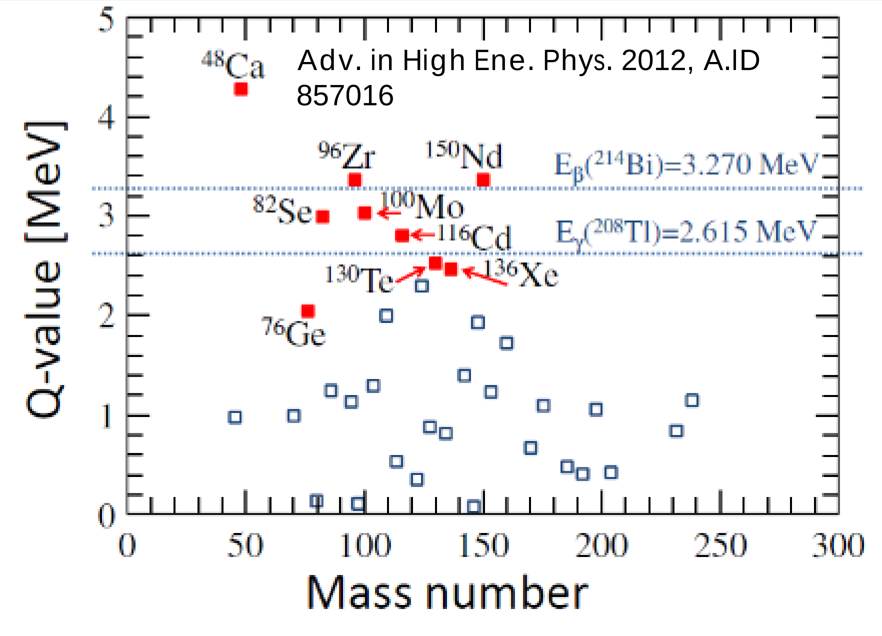
③ 0νββ with Majoron
(light neutral boson)
never observed – $\tau > 10^{22}$ y

Processes ② and ③ would imply new physics beyond the Standard Model
violation of total lepton number conservation

How many candidate nuclei?

Case of 2β⁻ processes →



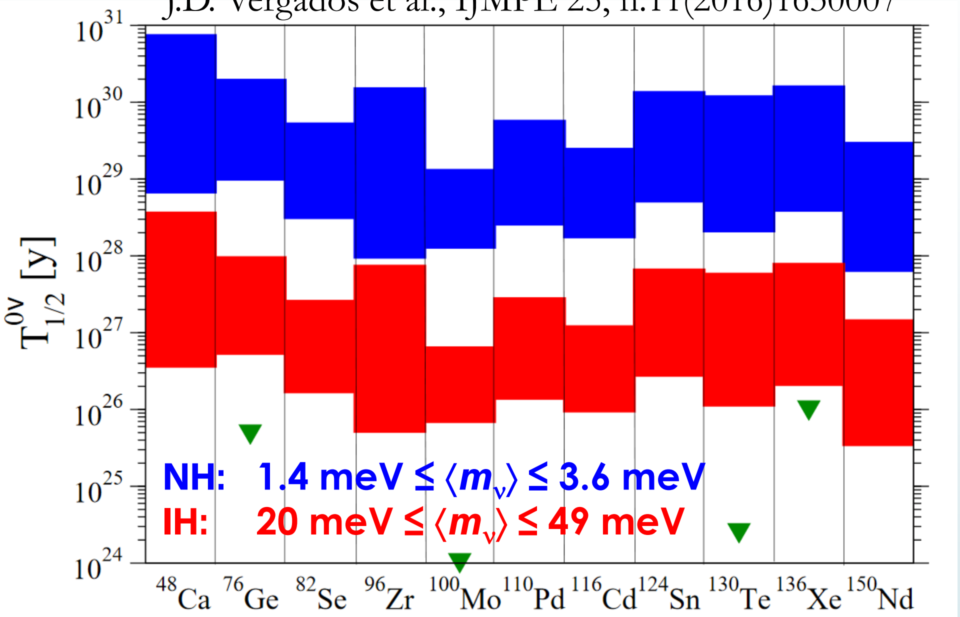
Investigation of 2β decay of ^{116}Cd with enriched $^{116}CdWO_4$ crystal scintillators

^{116}Cd

One of the best isotope for 0ν2β decay search:

- $Q_{\beta\beta}$ = 2813.44(13) keV
- δ = 7.49(18)%
- possible high isotopic enrichment
- promising theoretical calculation

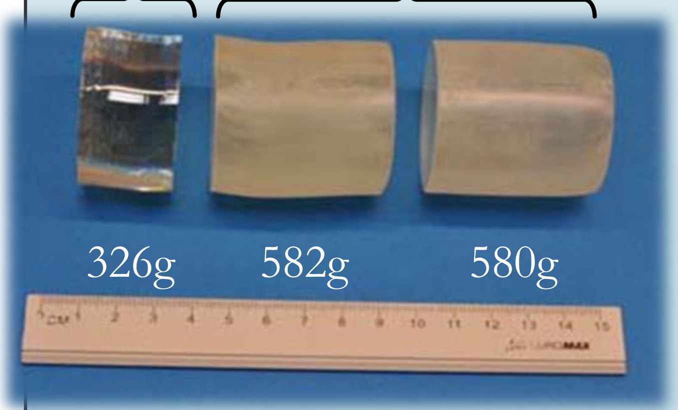
J.D. Vergados et al., IJMPE 25, n.11(2016)1630007



$^{116}CdWO_4$ 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)
- ✓ α/β discrimination capability

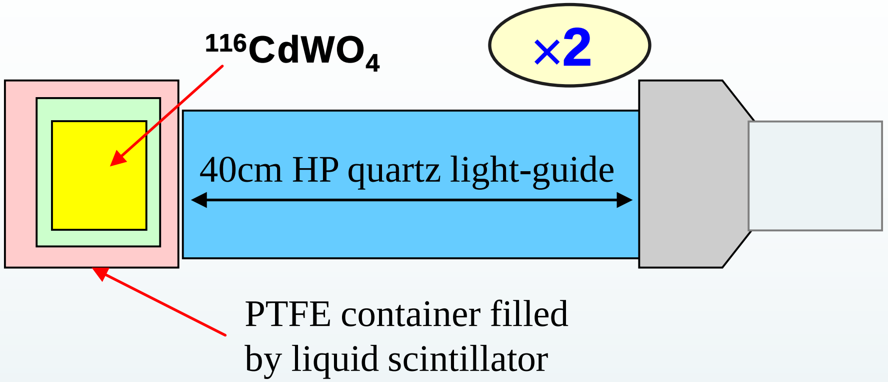


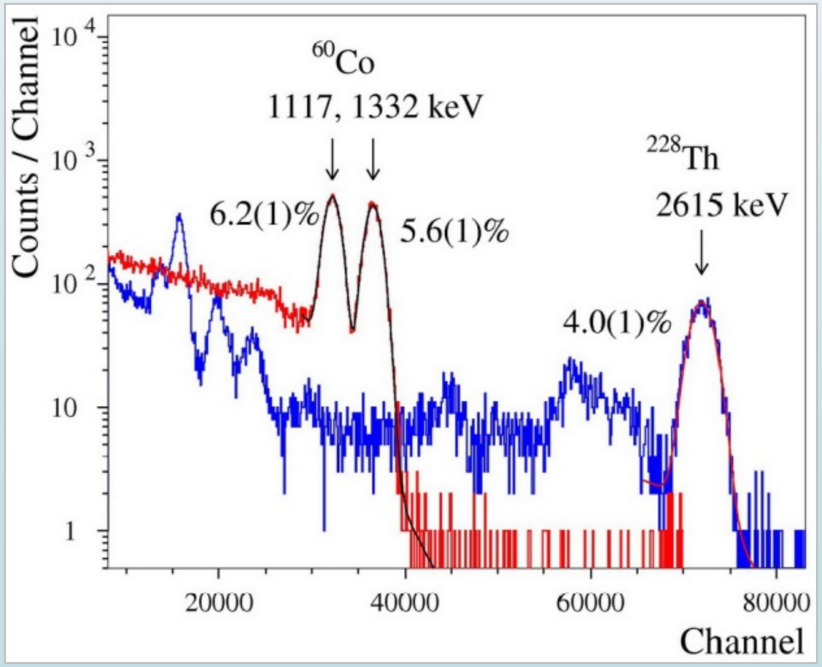
THE AURORA EXPERIMENT IN THE DAMA/R&D SET-UP

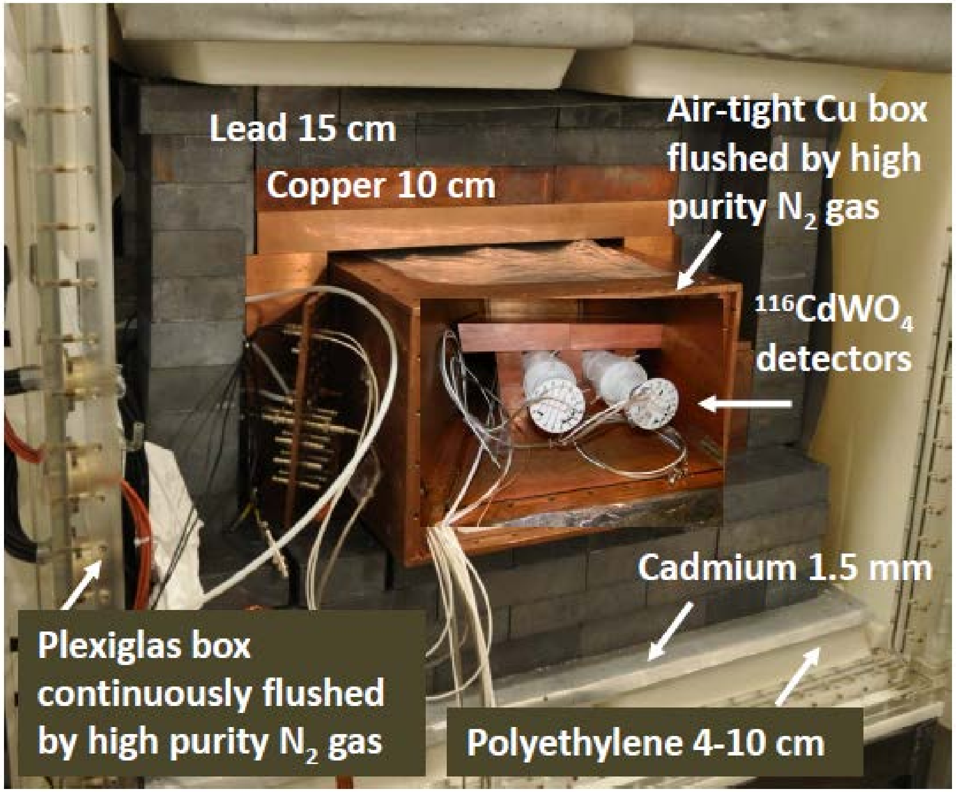
PRD 98 (2018) 092007

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**

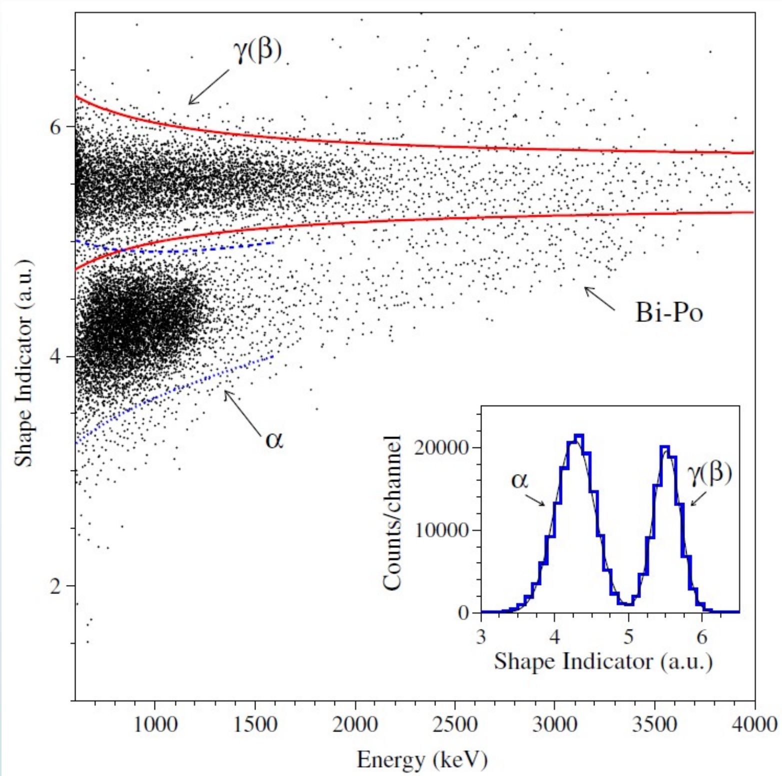






DATA ANALYSIS: PULSE SHAPE ANALYSIS - 1

Event-by-event DAQ based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the pulse shape over a time window of 100 μs from the $^{116}CdWO_4$ detectors



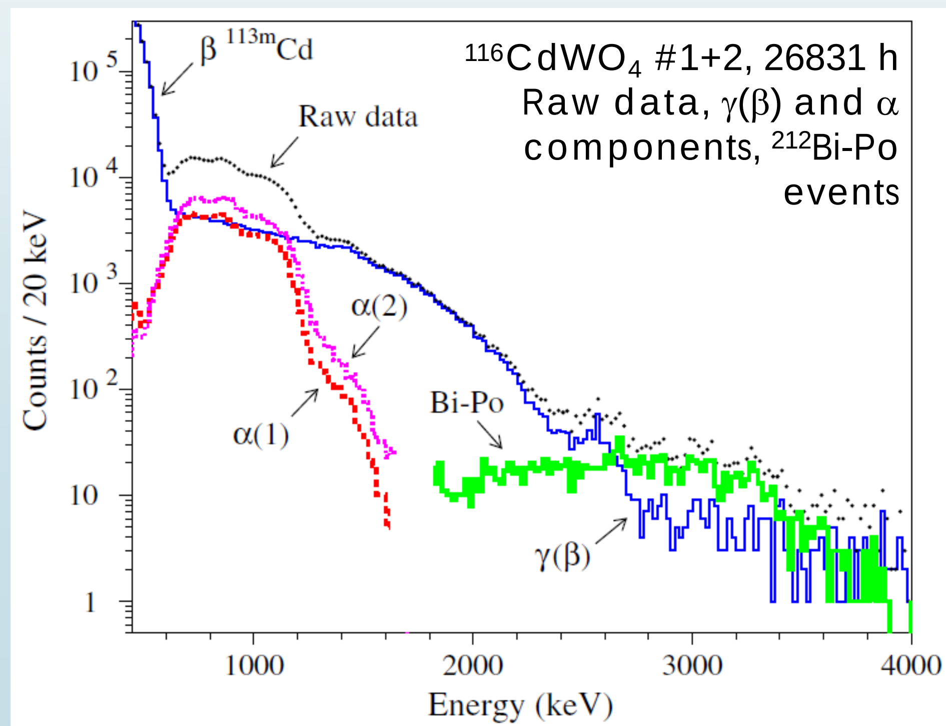
$^{116}CdWO_4$ detector #2, 26831 h.

Good discrimination ability.

$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k)$$

$$P(t) = [f_\alpha(t) - f_\gamma(t)]/[f_\alpha(t) + f_\gamma(t)]$$

$f(t_k)$ → amplitude at t_k
$P(t_k)$ → weight function
$f_{a,\gamma}(t_k)$ → reference pulse



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DATA ANALYSIS: PULSE SHAPE ANALYSIS - 2

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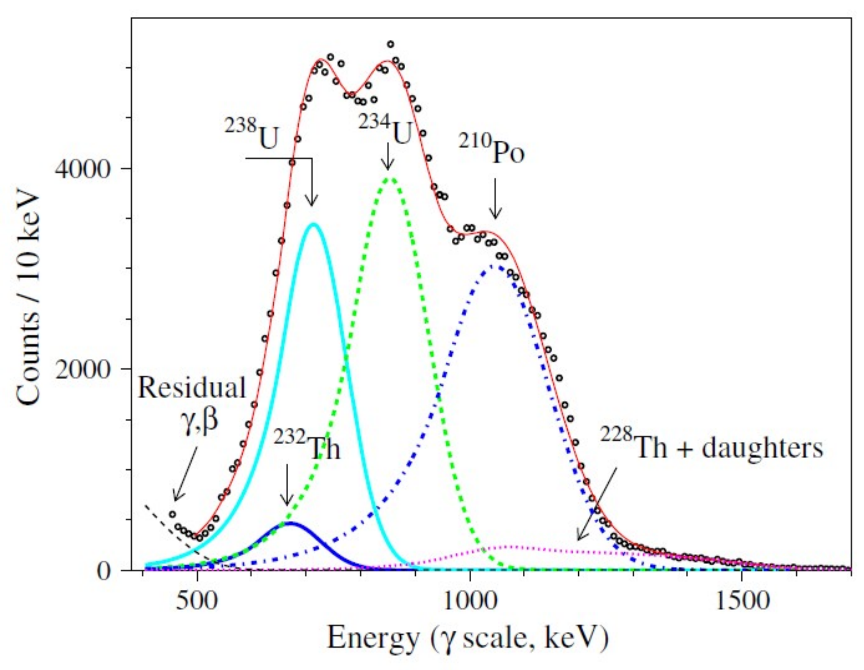
Radioactive contaminations of $^{116}CdWO_4$ crystal scintillators

Chain	Nuclide	Activity (mBq/kg)
	^{40}K	0.22(9)
	^{90}Sr – ^{90}Y	≤0.02
	^{110m}Ag	≤0.007
	^{116}Cd	1.138(5)
^{232}Th	^{232}Th	0.07(2)
	^{228}Ra	≤0.005
	^{228}Th	0.020(1)
^{235}U	^{227}Ac	≤0.002
^{238}U	^{238}U	0.58(4)
	^{234}U	0.6(1)
	^{230}Th	≤0.13
	^{226}Ra	≤0.006
	^{210}Pb	0.70(4)
Total α		2.14(2)



Spectrum of α events (26831 h, CWO-1 and CWO-2) and its individual components

DATA ANALYSIS: TIME-AMPLITUDE ANALYSIS OF FAST SUBCHAINS

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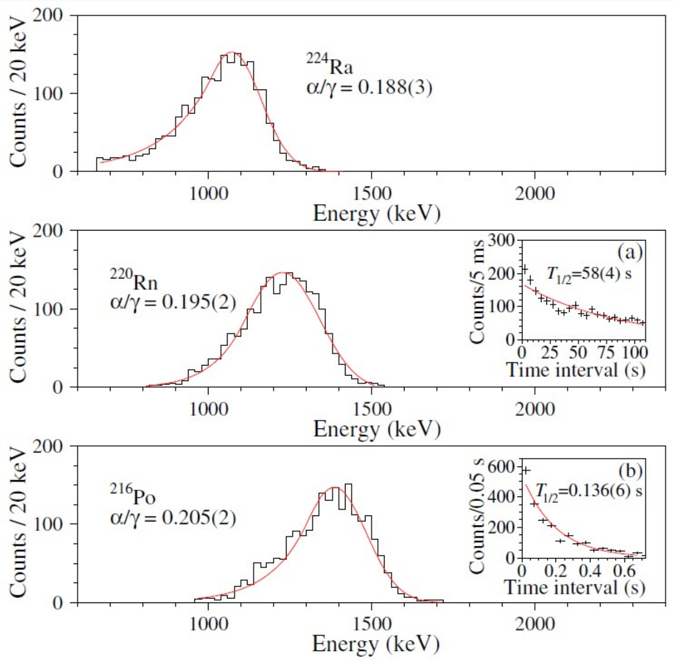
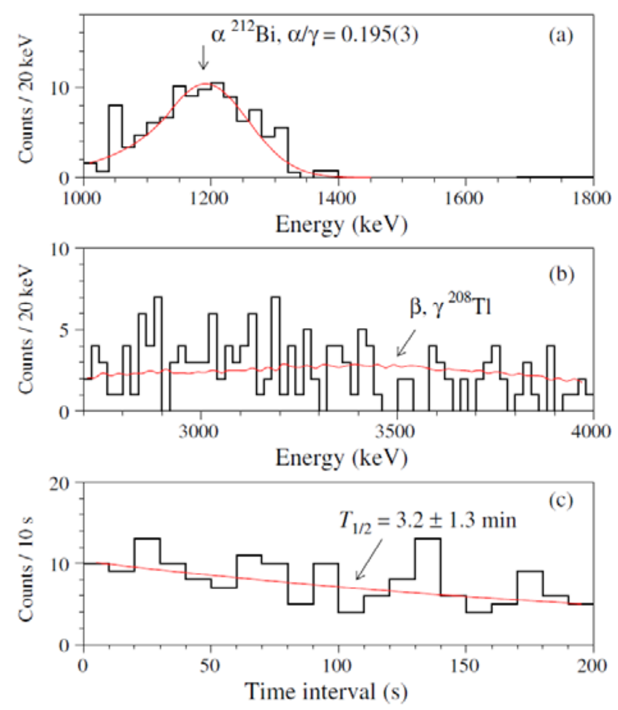
Selection of subchains: events with known energies and time differences

$$^{224}\text{Ra}(Q_\alpha = 5789 \text{ keV}; T_{1/2} = 3.632 \text{ d}) \rightarrow {}^{220}\text{Rn}(Q_\alpha = 6405 \text{ keV}; T_{1/2} = 55.6 \text{ s}) \rightarrow {}^{216}\text{Po} (Q_\alpha = 6906 \text{ keV}; T_{1/2} = 0.145 \text{ s}) \rightarrow {}^{212}\text{Pb}.$$



α peaks of ^{224}Ra, ^{220}Rn, ^{216}Po.
$T_{1/2}$: ^{220}Rn = 58(4) s; ^{216}Po = 0.136(6) s

$$^{212}\text{Bi}(Q_\alpha = 6207 \text{ keV}) \rightarrow {}^{208}\text{Tl}(Q_\beta = 4999 \text{ keV}, T_{1/2} = 3.053 \text{ min}) \rightarrow {}^{208}\text{Pb}$$



α peak of ^{212}Bi and
β distribution of ^{208}Tl

α/β ratio = 0.114(7) + 0.0133(12) E_α

DATA ANALYSIS: FRONT-EDGE ANALYSIS

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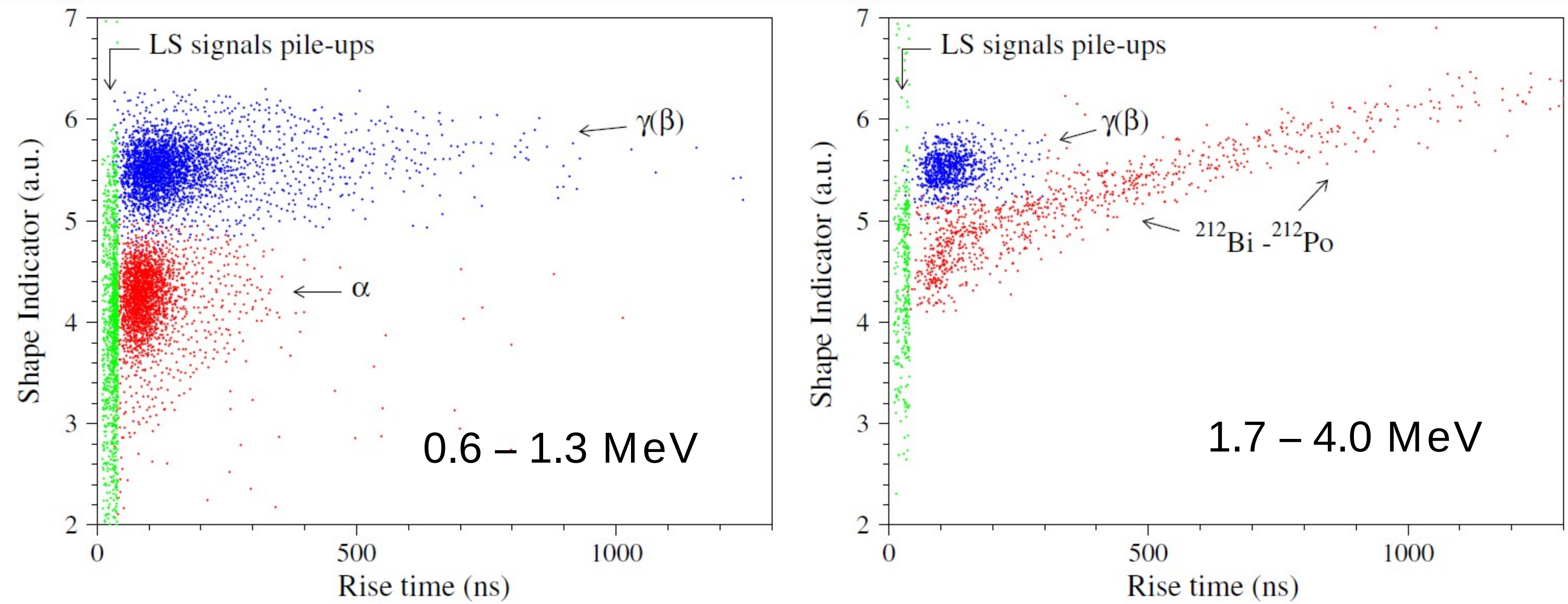
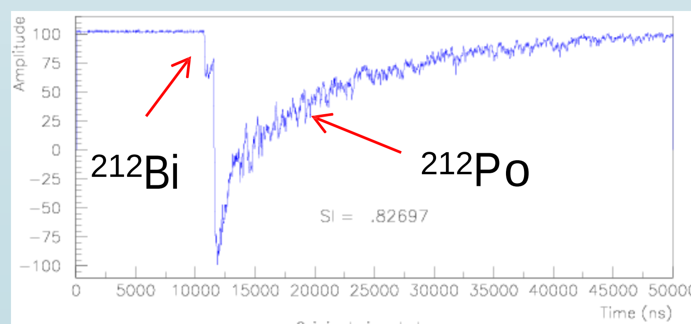
Front-edge parameter (rise time) = time between the signal origin and time of 0.7 of max value



In this way ^{212}Bi-^{212}Po events are selected

$$^{212}\mathrm{Bi}(Q_\beta = 2252\ \mathrm{keV}; T_{1/2} = 60.55\ \mathrm{m}) \rightarrow {}^{212}\mathrm{Po}(Q_\alpha = 8954\ \mathrm{keV}; T_{1/2} = 0.299\ \mu s) \rightarrow {}^{208}\mathrm{Pb}$$



(also pile-ups of CWOs with LS)

DATA ANALYSIS: RESULTS - 1

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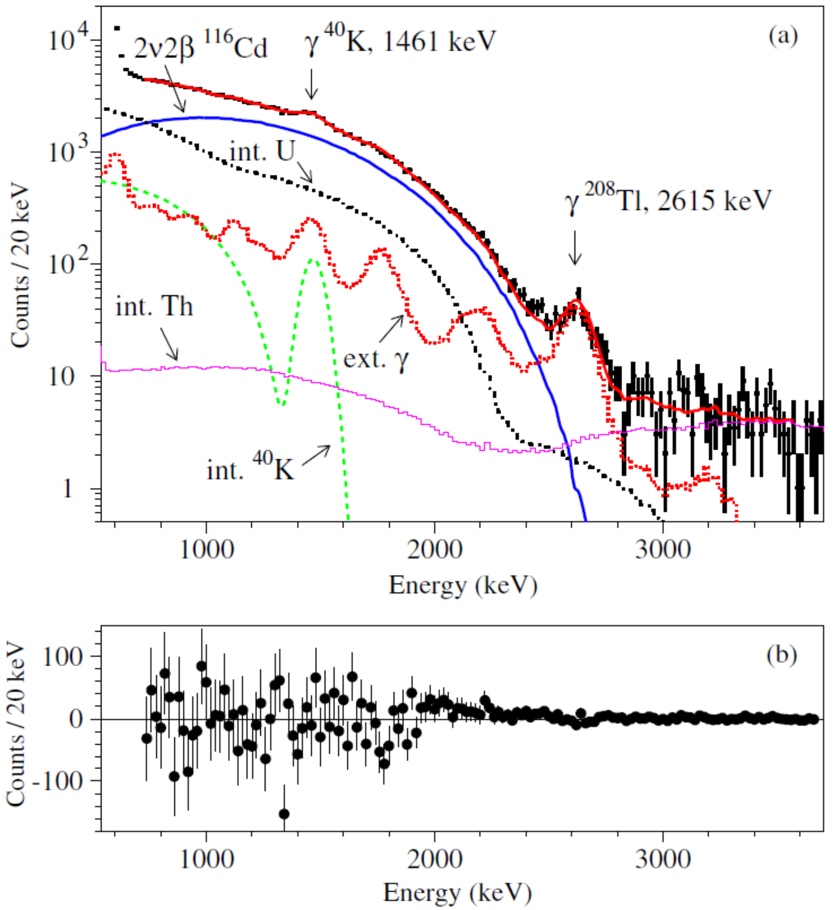
$2\beta2\nu$ decay of ^{116}Cd (g.s. to g.s.)

Selection of events: PSD and FE



$\gamma(\beta)$ energy spectrum, CWO-1 and CWO-2, 26831 h together with the main components

Background model:

1. internal contaminations of CWOs by ^{40}K, ^{90}Sr/^{90}Y, ^{110m}Ag, ^{232}Th, ^{238}U
2. external γ's from Cu shield, PMTs, quartz light-guides (^{40}K, Th/U)

Initial kinematics: DECAY0 generator

Simulations: EGS4

Starting point: 640–1600 keV (20 keV step)

Final point: 2800–3600 keV

χ^2/ndf = 1.15 – 1.75

Best fit (720 – 3560 keV, χ^2/ndf = 1.15):

92923±388 $2\beta2\nu$ events

(126341±527 in the whole spectrum)

$T_{1/2}(2\beta2\nu)$ = (2.630 ± 0.011(stat))×10^{19} yr

DATA ANALYSIS: RESULTS - 2

TABLE IV. Systematic uncertainties of $T_{1/2}$ (%).

Source	Contribution
Number of ^{116}Cd nuclei	± 0.12
PSD and front-edge cuts efficiency	± 1.2
Model of background	$^{+3.25}_{-2.93}$
Localization of radioactive contaminations	$^{+1.54}_{-2.63}$
Interval of the fit	$^{+0.34}_{-1.02}$
Energy scale instability	± 1.72
$2\nu 2\beta$ spectral shape	± 1.0
Total systematic error	$^{+4.30}_{-4.69}$

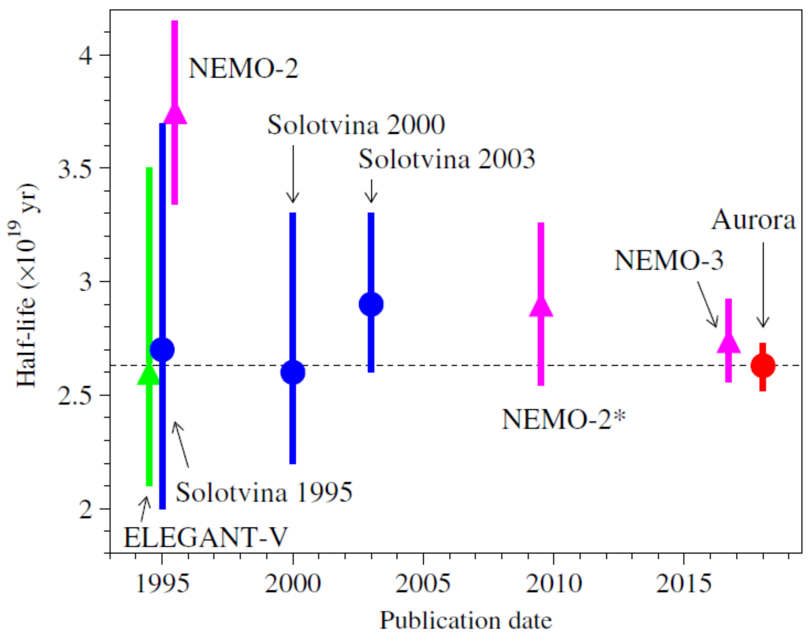
$$\mathbf{NME_{eff} = 1/(G_{2\nu}\times T_{1/2})^{1/2}}$$

TABLE V. Effective nuclear matrix elements for $2\nu 2\beta$ decay of ^{116}Cd to the ground state of ^{116}Sn obtained by using different calculations of the phase space factors.

Phase space factor (10^{-21} yr^{-1}), Reference	Effective nuclear matrix element
2764 [68]	$0.1173^{+0.0027}_{-0.0024}$
3176 [68] (SSD model)	$0.1094^{+0.0025}_{-0.0023}$
2688 [69]	$0.1189^{+0.0027}_{-0.0025}$

[68] J. Kotila and F. Iachello, PRC 85 (2012) 034316
[69] M. Mirea et al., Rom. Rep. Phys. 67 (2015) 872

$$\mathbf{T_{1/2}(2\beta 2\nu) = (2.630 \pm 0.011(stat)^{+0.113}_{-0.123}(sys))\times 10^{19}\ yr}$$

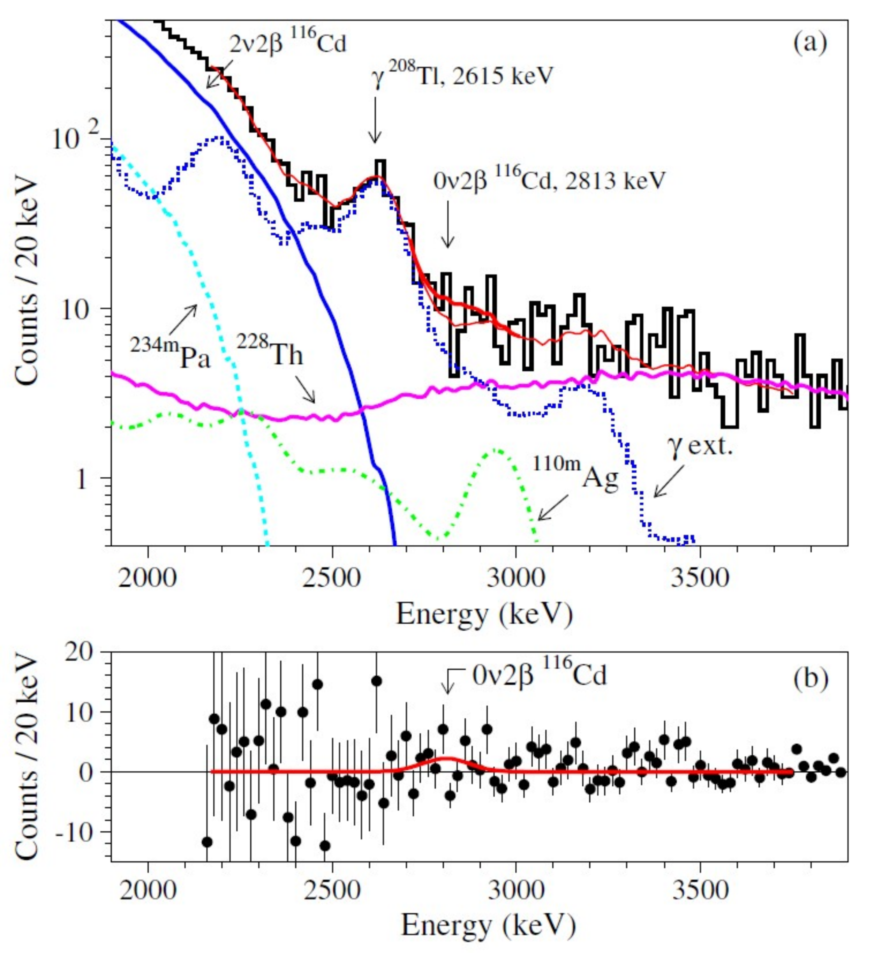


ELEGANT: J. Phys. Soc. Japan 64(1995)339
Solotvina 1995: Phys. Lett. B 344(1995)72
NEMO-2: Z. Phys. C 72(1996)239
Solotvina (2000): PRC 62(2000)045501
Solotvina (2003): PRC 68(2003)035501
NEMO-2* (recalc.): PRC 81(2010)035501
NEMO-3: PRD 95(2017)012007
AURORA: PRD 98 (2018) 092007

DATA ANALYSIS: RESULTS - 3

$2\beta0\nu$ decay of ^{116}Cd (g.s. to g.s.) PRD 98 (2018) 092007

26831 h + 8493 h from previous stage with background rate ~0.1 counts/(keV kg yr) at 2.7–2.9 MeV = 35324 h

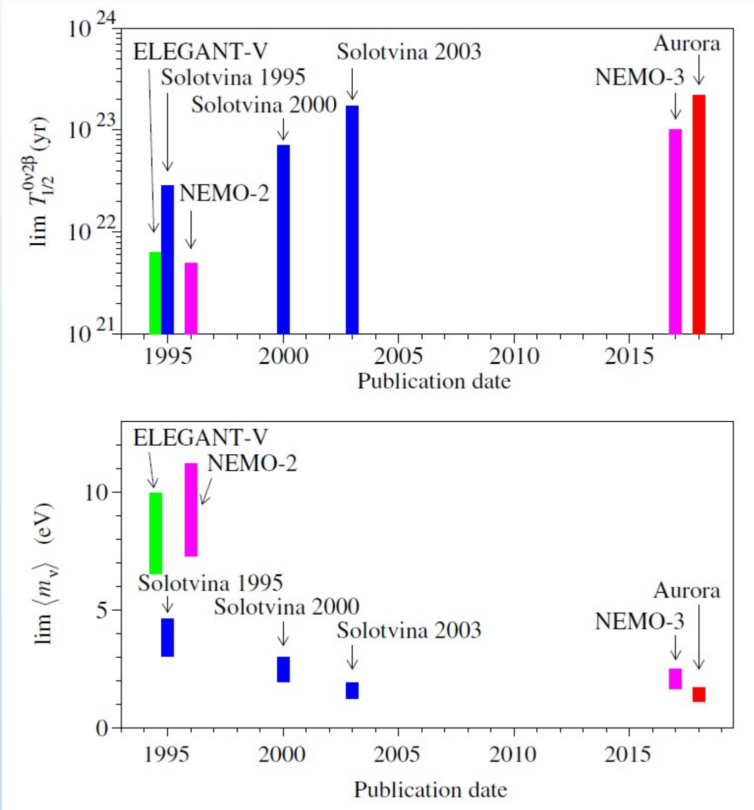


$\gamma(\beta)$ energy spectrum, *CWO-1* and CWO-2, 35324 h together with the main components

Best fit: 2160–3740 keV, χ^2/ndf = 1.01

S =–4.5±14.2 → S < 19.1 counts

$T_{1/2}(2\beta0\nu)$ > 2.2×10^{23} yr 90% C.L.

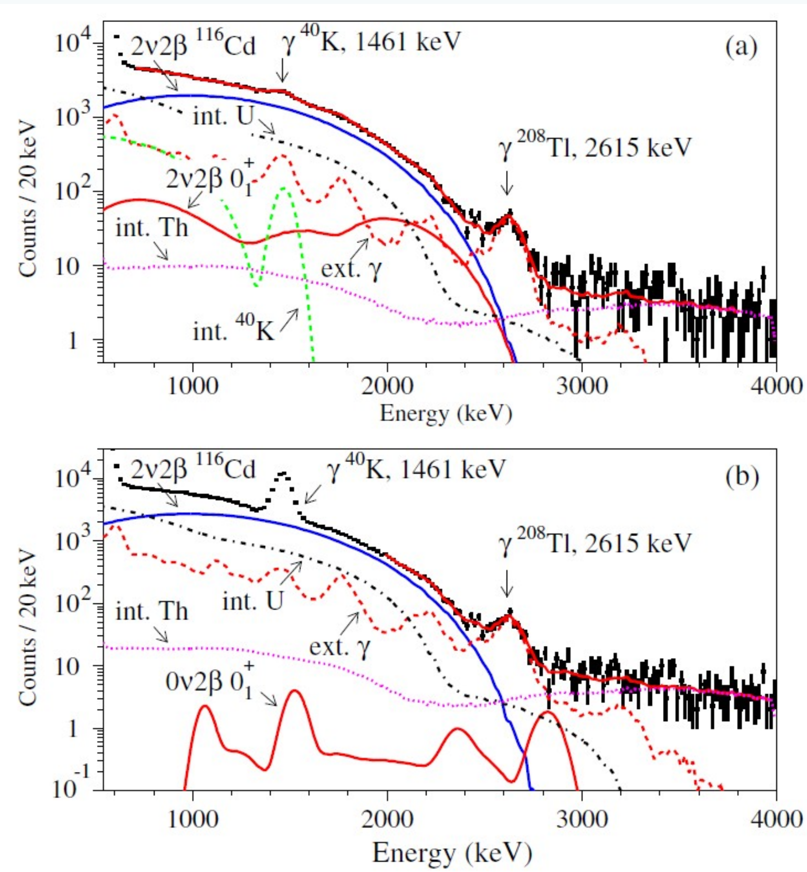


m_ν-λ-η ellipsoid: limits on m_ν, λ, η

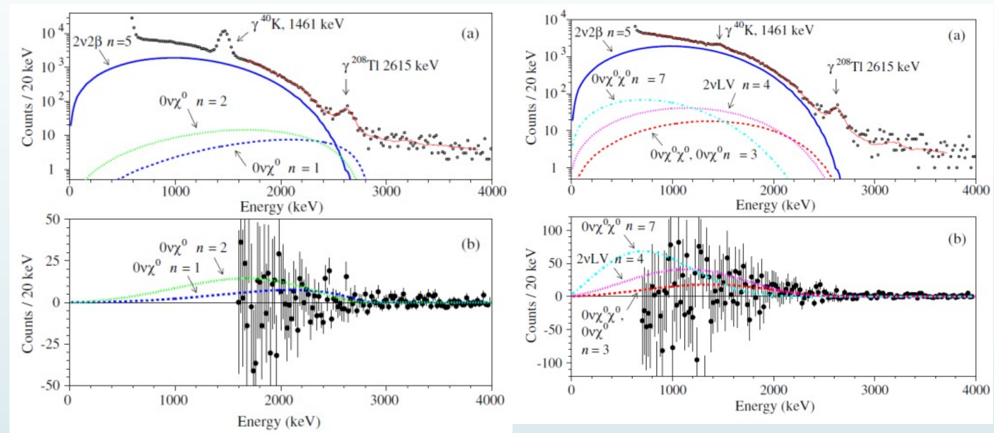
DATA ANALYSIS: RESULTS - 4

2β decays to excited levels, 2β0ν decays with majoron(s) emission, Lorentz violating 2β2ν decay

Fit of experimental spectrum by background model + 2β2ν distribution + additional distribution for transition to excited state



Fit for 2β2ν and 2β0ν decays to the first 0_1^+ level of ^{116}Sn (1757 keV)



Fits for majorons with spectral index SI = 1, 2 (at higher energies) and SI = 3, 4, 7 (at lower energies)

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AURORA RESULTS

TABLE VI. Summary of the obtained results on 2β processes in ^{116}Cd. The limits are given at 90% C.L., except of the results of [47], obtained at 68% C.L.

Decay mode	Transition, level of ^{116}Sn (keV)	$T_{1/2}$ (yr)	Best previous limits (yr) Reference
2ν	g.s.	$(2.63^{+0.11}_{-0.12})\times10^{19}$ yr	see Table I and Fig. 12
2ν	2^+ (1294)	$\geq 9.8\times10^{20}$	$\geq 2.3\times10^{21}$ [48]
2ν	0^+ (1757)	$\geq 5.9\times10^{20}$	$\geq 2.0\times10^{21}$ [48]
2ν	0^+ (2027)	$\geq 1.1\times10^{21}$	$\geq 2.0\times10^{21}$ [48]
2ν	2^+ (2112)	$\geq 2.5\times10^{21}$	$\geq 1.7\times10^{20}$ [47]
2ν	2^+ (2225)	$\geq 7.5\times10^{21}$	$\geq 1.0\times10^{20}$ [47]
0ν	g.s.	$\geq 2.2\times10^{23}$	$\geq 1.7\times10^{23}$ [32]
0ν	2^+ (1294)	$\geq 7.1\times10^{22}$	$\geq 2.9\times10^{22}$ [32]
0ν	0^+ (1757)	$\geq 4.5\times10^{22}$	$\geq 1.4\times10^{22}$ [32]
0ν	0^+ (2027)	$\geq 3.1\times10^{22}$	$\geq 0.6\times10^{22}$ [32]
0ν	2^+ (2112)	$\geq 3.7\times10^{22}$	$\geq 1.7\times10^{20}$ [47]
0ν	2^+ (2225)	$\geq 3.4\times10^{22}$	$\geq 1.0\times10^{20}$ [47]
$0\nu\chi^0 n=1$	g.s.	$\geq 8.2\times10^{21}$	$\geq 8.5\times10^{21}$ [45]
$0\nu\chi^0 n=2$	g.s.	$\geq 4.1\times10^{21}$	$\geq 1.7\times10^{21}$ [32]
$0\nu\chi^0 n=3$	g.s.	$\geq 2.6\times10^{21}$	$\geq 0.8\times10^{21}$ [32]
$0\nu\chi^0\chi^0 n=3$	g.s.	$\geq 2.6\times10^{21}$	$\geq 0.8\times10^{21}$ [32]
$2\nu LV n=4$	g.s.	$\geq 1.2\times10^{21}$	...
$0\nu\chi^0\chi^0 n=7$	g.s.	$\geq 8.9\times10^{20}$	$\geq 4.1\times10^{19}$ [77]

TABLE VII. Limits on lepton-number violating parameters. The limits are given at 90% C.L.

Parameter	Limit
Effective light Majorana neutrino mass $\langle m_\nu \rangle$	$\leq (1.0-1.7)$ eV
Effective heavy Majorana neutrino mass $\lvert\langle m_{\nu_h}^{-1}\rangle\rvert^{-1}$	$\geq(10-28)\times10^6$ GeV
Right-handed current admixture $\langle\lambda\rangle$	$\leq (1.8-22)\times10^{-6}$
Right-handed current admixture $\langle\eta\rangle$	$\leq (1.6-21)\times10^{-8}$
Coupling constant of neutrino with majoron $\langle g_{ee}\rangle$	
χ^0, $n=1$	$\leq (6.1-9.3)\times10^{-5}$
χ^0, $n=3$	$\leq 7.7\times10^{-2}$
$\chi^0\chi^0, n=3$	$\leq (0.69-6.9)$
$\chi^0\chi^0, n=7$	$\leq (0.57-5.7)$
R-parity violating parameter λ'_{111}	$\leq 2.5\times10^{-4}\times f$ (see text)
Lorentz-violating parameter $\mathring{a}^{(3)}_{\rm of}$	$\leq 4.0\times10^{-6}$ GeV

NME for m_ν:
J. Barea et al., PRC 91 (2015 034304 (IBM)
F. Simkovic et al., PRC 87 (2013) 045501 (QRPA)
N.L. Vaquero et al., PRL 111 (2013) 142501 (EDFT)
J. Hyvärinen et al., PRC 91 (2015) 024613 (pnQRPA)
L.S. Song et al., PRC 95 (2017) 024305 (EDFT)

PSF:
J. Kotila, F. Iachello, PRC 85 (2012) 034316

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CONCLUSIONS

After near 5 yr of data taking at LNGS (3600 m w.e.), the Aurora experiment to investigate 2β processes in ^{116}Cd with 1.162 kg of enriched (82%) $^{116}CdWO_4$ scintillators is finished

$T_{1/2}$ for 2β2ν is precisely measured: $T_{1/2}(2\beta2\nu) = 2.63^{+0.11}_{-0.12}\times10^{19}$ yr

The most stringent limit for 2β0ν is obtained: $T_{1/2}(2\beta0\nu) > 2.2\times10^{23}$ yr, equivalent to Majorana ν mass limits: $m_\nu < 1.0 - 1.7$ eV (depending on NME)

Limits on 2β2ν and 2β0ν decays to excited levels: $T_{1/2} > 10^{20} - 10^{22}$ yr

Limits on 2β0ν decays with different majorons: $T_{1/2} > 10^{21} - 10^{22}$ yr

Limits on right-handed admixtures in weak interaction, heavy ν mass, majoron-neutrino coupling constants, Lorentz-violating 2β2ν decay

R&D's in progress to achieve even higher sensitivity

Thanks for your attention