DAMA Collaboration
(Roma2, Roma, LNGS, IHEP/Beijing)
& INR-Kiev
http://people.roma2.infn.it/dama

Searches for non-paulian transitions in highly radiopure NaI(Tl): previous results and perspectives

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Roma2,Roma1,LNGS,IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India
LIBRA in DAMA
DAMA: an observatory for rare processes @LNGS
DAMA/R&D
DAMA/LXe
low bckg DAMA/Ge for sampling meas.
meas. with 100Mo
DAMA/NaI
DAMA/LIBRA
http://people.roma2.infn.it/dama

DAMA/LXe: results on rare processes

NIMA482(2002)728

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering — PLB387(1996)222, NJP2(2000)15.1
- Neutron calibration — PLB436(1998)379, EPJdirectC11(2001)1
- ^{129}Xe *vs* ^{136}Xe by using PSD → SD *vs* SI signals to increase the sensitivity on the SD component — foreseen/in progress

Other rare processes:

- Electron decay into invisible channels — Astrop.P.5(1996)217
- Nuclear level excitation of ^{129}Xe during CNC processes — PLB465(1999)315
- N, NN decay into invisible channels in ^{129}Xe — PLB493(2000)12
- Electron decay: $e^{-} \to \nu_e \gamma$ — PRD61(2000)117301
- 2β decay in ^{136}Xe — Xenon01
- 2β decay in ^{134}Xe — PLB527(2002)182
- Improved results on 2β in ^{134}Xe,^{136}Xe — PLB546(2002)23
- CNC decay ^{136}Xe → ^{136}Cs — Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe — EPJA27 s01 (2006) 35

DAMA/R&D set-up: results on rare processes

- Particle Dark Matter search with CaF_2(Eu) — NPB563(1999)97, Astrop.Phys.7(1997)73

- 2β decay in ^{136}Ce and in ^{142}Ce — Il Nuov.Cim.A110(1997)189
- 2EC2ν ^{40}Ca decay — Astrop. Phys. 7(1997)73
- 2β decay in ^{46}Ca and in ^{40}Ca — NPB563(1999)97
- 2β^{+} decay in ^{106}Cd — Astrop.Phys.10(1999)115
- 2β and β decay in ^{48}Ca — NPA705(2002)29
- 2EC2ν in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce — NIMA498(2003)352
- 2β^{+} 0ν and EC β^{+} 0ν decay in ^{130}Ba — NIMA525(2004)535
- Cluster decay in $LaCl_3$(Ce) — NIMA555(2005)270
- CNC decay ^{139}La → ^{139}Ce — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15
- β decay of ^{113}Cd — PRC76(2007)064603
- ββ decay of ^{64}Zn — PLB658(2008)193
- ββ decay of ^{108}Cd and ^{114}Cd — EPJA36(2008)167

DAMA/Ge & LNGS Ge facility

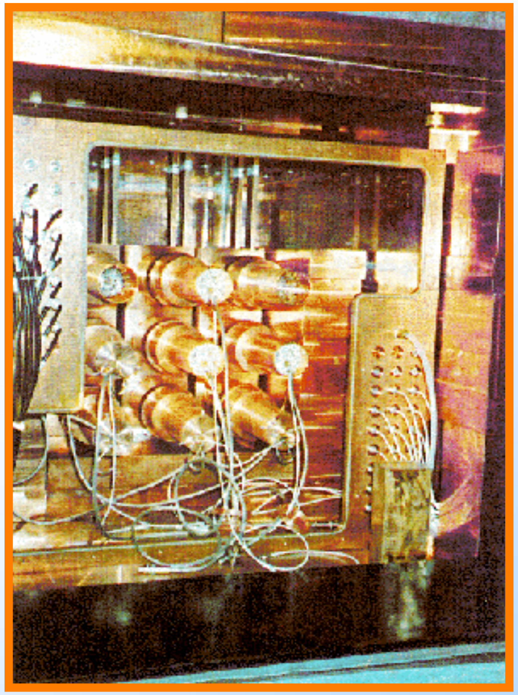
- RDs on highly radiopure NaI(Tl) set-up;
- several RDs on low background PMTs;
- qualification of many materials
- measurements with a $Li_6Eu(BO_3)_3$ crystal (NIMA572(2007)734)
- measurements with ^{100}Mo sample investigating ββ decay in the 4π low-bckg HP Ge facility of LNGS (to appear on Nucl. Phys. and Atomic Energy)
- search for ^{7}Li solar axions (NPA806(2008)388)

+Many other meas. already scheduled for near future

Main Features of the former DAMA/NaI

Il Nuovo Cim. A112 (1999) 545-575, EPJC18(2000)283,
Riv. N. Cim. 26 n.1 (2003)1-73, IJMPD13(2004)2127

- Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- PMTs: Each crystal coupled - through 10cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI9265B53/FL (special development) 3" diameter PMTs working in coincidence.
- Detectors inside a sealed Cu box maintained in HP Nitrogen atmosphere in slight overpressure
- Very low radioactive shields: 10 cm of Cu, 15 cm of Pb + shield from neutrons: Cd foils + polyethylene/paraffin+ ~ 1 m concrete moderator largely surrounding the set-up
- Installation sealed: A plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure. Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm^2/s permeability).Three levels of sealing.
- Installation in air conditioning + huge heat capacity of shield
- Calibration using the upper glove-box (equipped with compensation chamber) in HP Nitrogen atmosphere in slight overpressure calibration $\rightarrow$ in the same running conditions as the production runs.
- Energy and threshold: Each PMT works at single photoelectron level. Energy threshold: 2 keV (from X-ray and Compton electron calibrations in the keV range and from the features of the noise rejection and efficiencies). Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
- Pulse shape recorded over 3250 ns by Transient Digitizers.
- Monitoring and alarm system continuously operating by self-controlled computer processes.



+ electronics and DAQ fully renewed in summer 2000

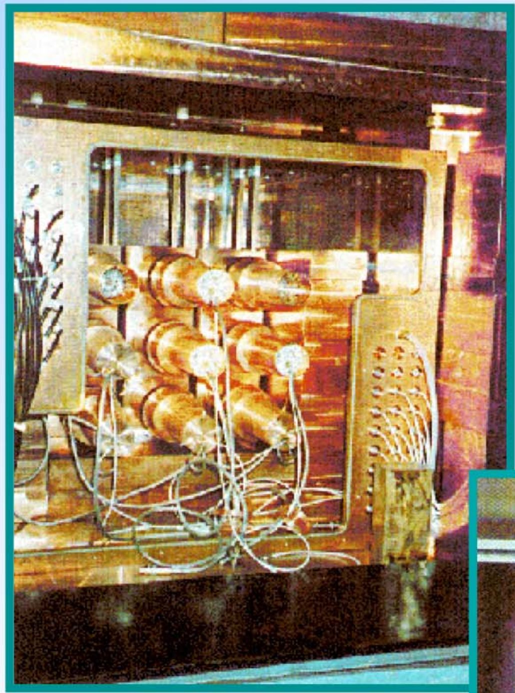
Main procedures of the DAMA data taking for the DMp annual modulation signature

- data taking of each annual cycle starts from autumn/winter (when $\cos\omega(t-t_0)\approx0$) toward summer (maximum expected).
- routine calibrations for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration from ^{210}Pb (~ 7 days periods) + periodical Compton calibrations, etc.
- continuous on-line monitoring of all the running parameters with automatic alarm to operator if any out of allowed range.

The former DAMA/NaI(Tl)~100 kg

(out of operation on July 2002, still producing results)

Performances: N.Cim.A112(1999)545 EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1, IJMPD13(2004)2127



Results on rare processes:

- Possible Pauli exclusion principle violation PLB408(1997)439
- CNC processes PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) PLB460(1999)235
- Search for solar axions PLB515(2001)6
- Exotic Matter search EPJdirect C14(2002)1
- Search for superdense nuclear matter EPJA23(2005)7
- Search for heavy clusters decays EPJA24(2005)51

Results on DM particles:

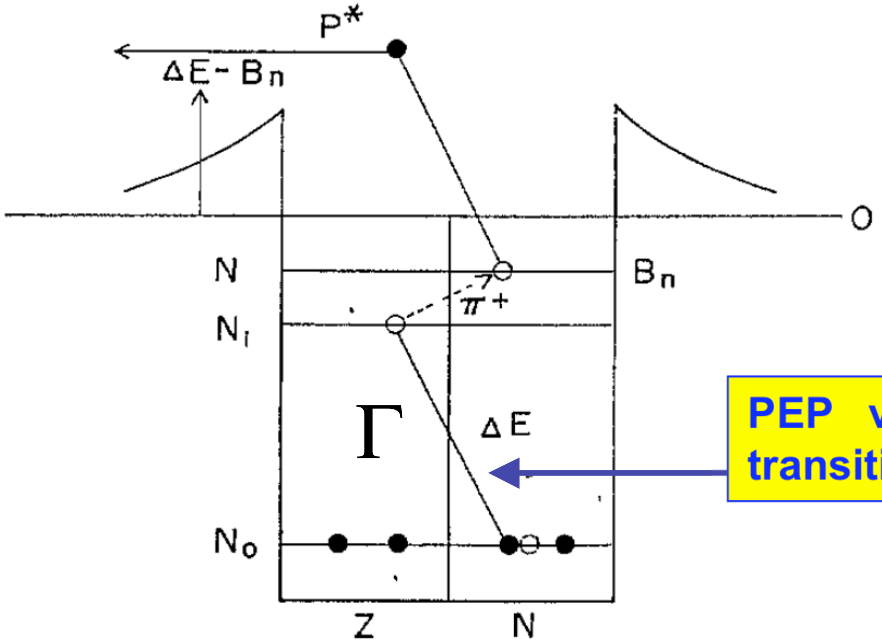
- PSD PLB389(1996)757
- Investigation on diurnal effect N.Cim.A112(1999)1541
- Exotic Dark Matter search PRL83(1999)4918
- Annual Modulation Signature
  PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23,EPJ C18(2000)283, PLB509(2001)197, EPJ C23 (2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1-73, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125.

data taking completed on July 2002

total exposure collected in 7 annual cycles **107731 kg×d**

1) Search for non-paulian nuclear processes

Proton emission
$E_p > 10$ MeV



Example of a process violating PEP: deexcitation of a nucleon from the shell N_i to the N_o lower (full) shell. The energy is converted to another nucleon at shell N through strong interaction, resulting to excitation to the unbound region.
(analogy: Auger emission)

PEP violating transition

PEP violation parameter (mixing probability of non fermion statistics)

$$\Gamma = \delta^2 \tilde{\Gamma}$$

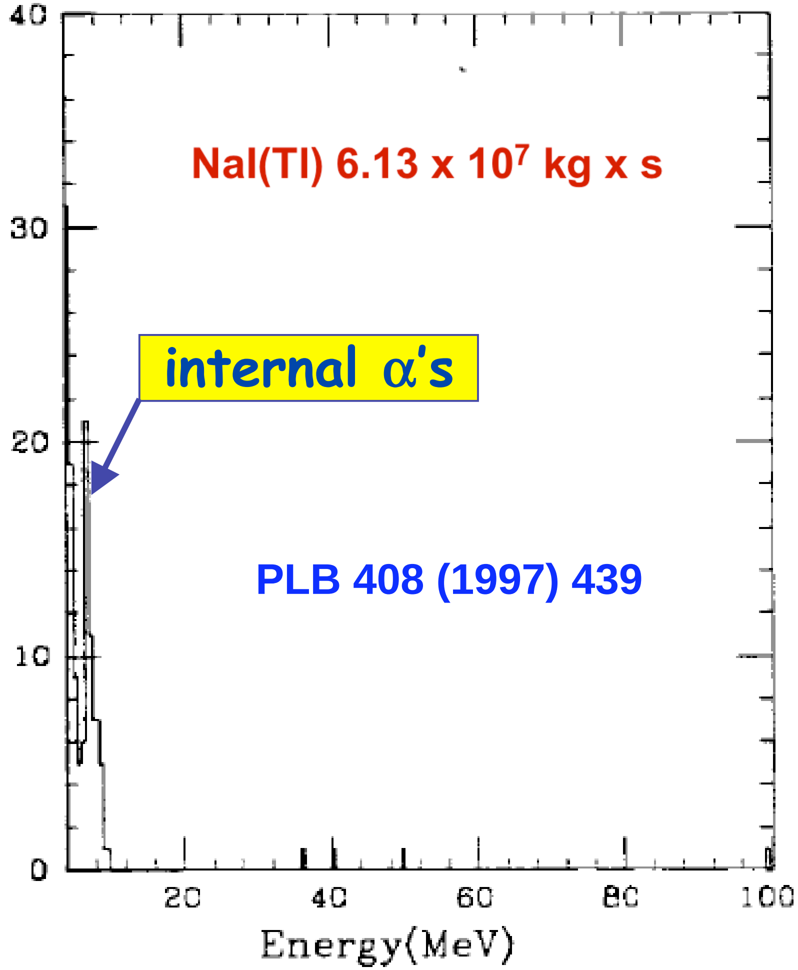
PEP violating transition width

PEP allowed transition width (as if the state N_o would be empty)

1) Search for non-paulian nuclear processes

PLB 408 (1997) 439

Example of a previous results with ≈ 100 Kg low background DAMA/NaI



N x t = 2.46 10^{32} nuclei x s

0 events in the 10 - 36 MeV range

$$\lambda = \lambda(^{23}\mathrm{Na}) + \lambda(^{127}\mathrm{I}) \lesssim 1.14(\epsilon N t)^{-1}$$

є proton detection efficiency ≈ 100%

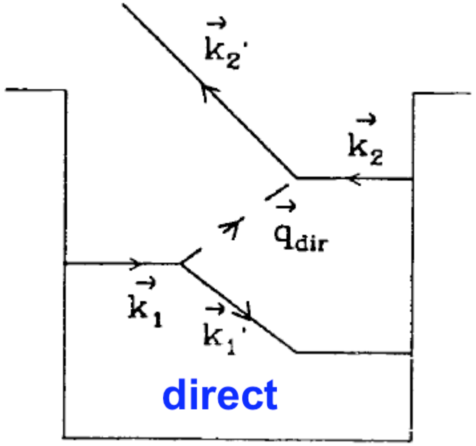
$$\lambda \leq 4.6 \times 10^{-33} s^{-1} \;\; (68\% \;\; C.L.)$$

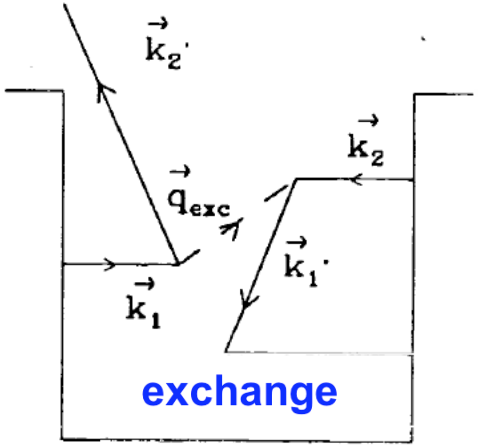
$$\Gamma = \Gamma(^{23}\mathrm{Na}) + \Gamma(^{127}\mathrm{I}) = \hbar\lambda \lesssim 3.0 \cdot 10^{-54}\ \mathrm{MeV}$$

1) Search for non-paulian nuclear processes

PLB 408 (1997) 439

Calculation of PEP allowed transition $\tilde{\Gamma}$



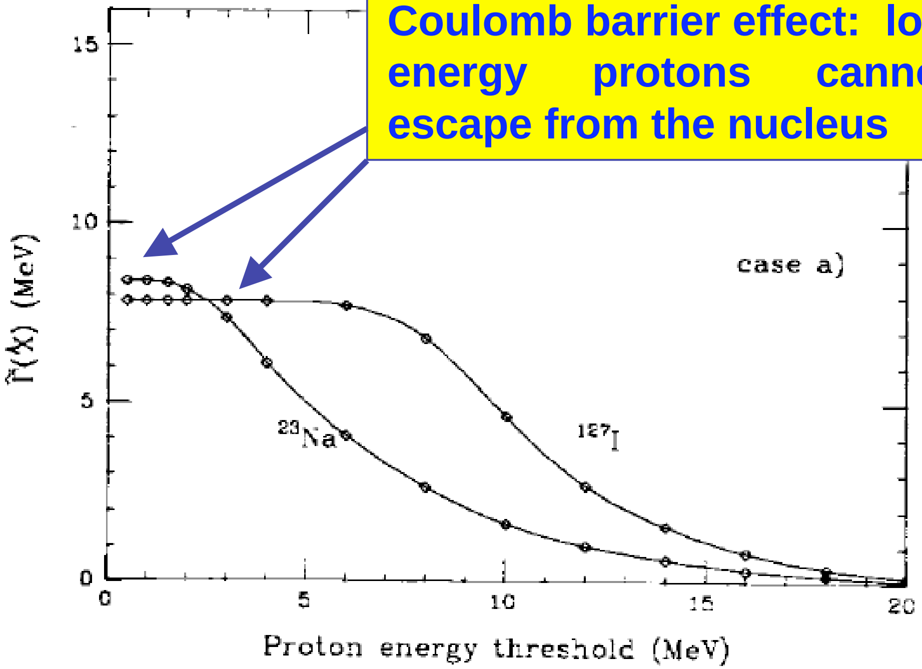


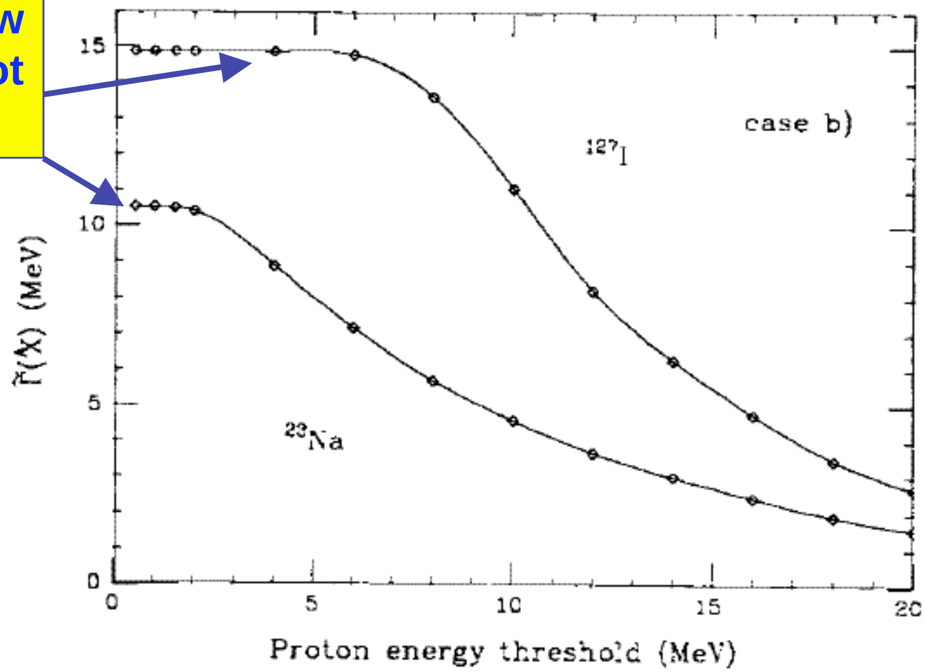
Momentum distribution function of nucleons in the bound state calculated in 2 cases:

a) Fermi distribution k_f = 255MeV/c

b) "realistic" distribution functions accounting for correlation effects (PRC43(1991)1155 very similar for all nuclei with A>12 used the case of ^{56}Fe)

Coulomb barrier effect: low energy protons cannot escape from the nucleus





1) Search for non-paulian nuclear processes

PLB 408 (1997) 439

Width calculated for escape and tunneling prob. of the excited proton $g_W(k) = g_c(k) = 1$

average escape prob. of the excited proton

Models for momentum distribution function

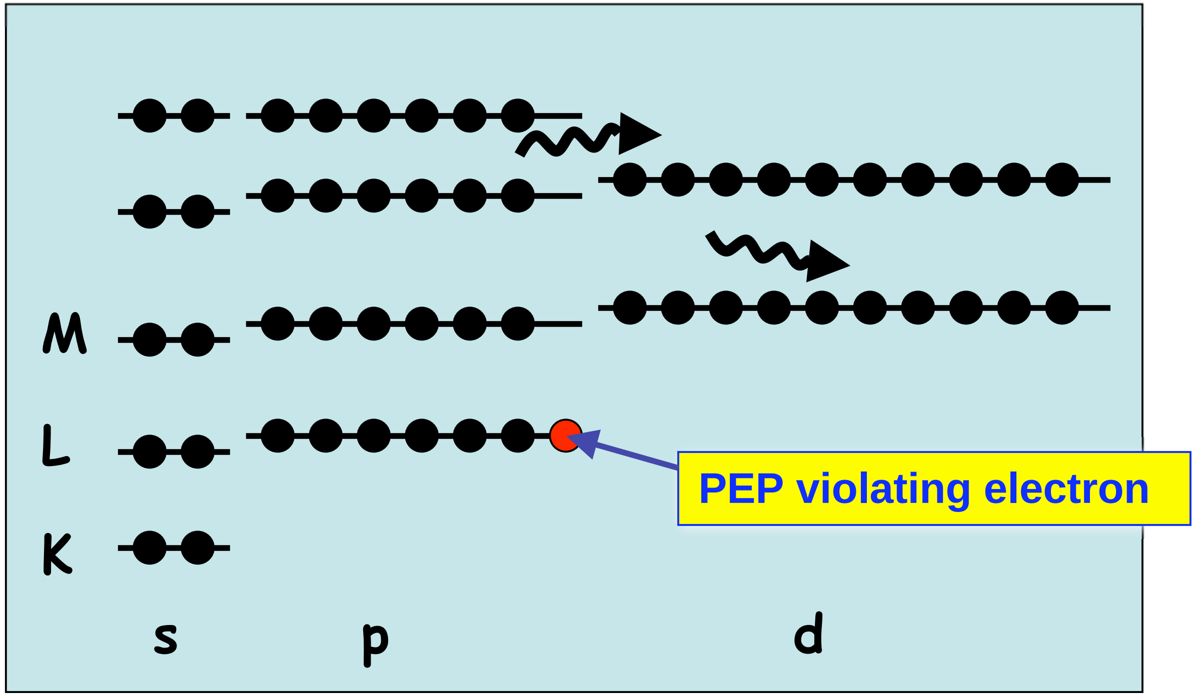
Case	^AX	E_{th} (MeV)	$\tilde{\Gamma}_0$ (MeV)	$\langle g_W \rangle$	$\tilde{\Gamma}$ (MeV)	Upper limit for δ^2
a)	^{23}Na	10	3.90	0.42	1.65	$4.8 \cdot 10^{-55}$
	^{127}I	10	16.0	0.29	4.64	
a)	^{23}Na	18	0.60	0.32	0.19	$5.0 \cdot 10^{-54}$
	^{127}I	18	1.65	0.25	0.41	
b)	^{23}Na	10	14.2	0.32	4.59	$1.9 \cdot 10^{-55}$
	^{127}I	10	76.6	0.14	11.1	
b)	^{23}Na	18	8.22	0.23	1.90	$5.6 \cdot 10^{-55}$
	^{127}I	18	44.6	0.08	3.49	

Limits on δ^2 are strongly model dependent; a cautious approach could be to consider: $\delta^2 \leqslant 10^{-54}$

Assuming Γ to have the same threshold dependence of $\tilde{\Gamma}$ ⇒ Lower limit on the mean life for non-paulian proton emission: $\tau > 0.7 \times 10^{25}$ y for ^{23}Na, $\tau > 0.9 \times 10^{25}$ y for ^{127}I

2) Search for non-paulian electronic transitions to L-shell

Electronic configuration schema of I anion (54 electrons) in Na^+I^- crystal

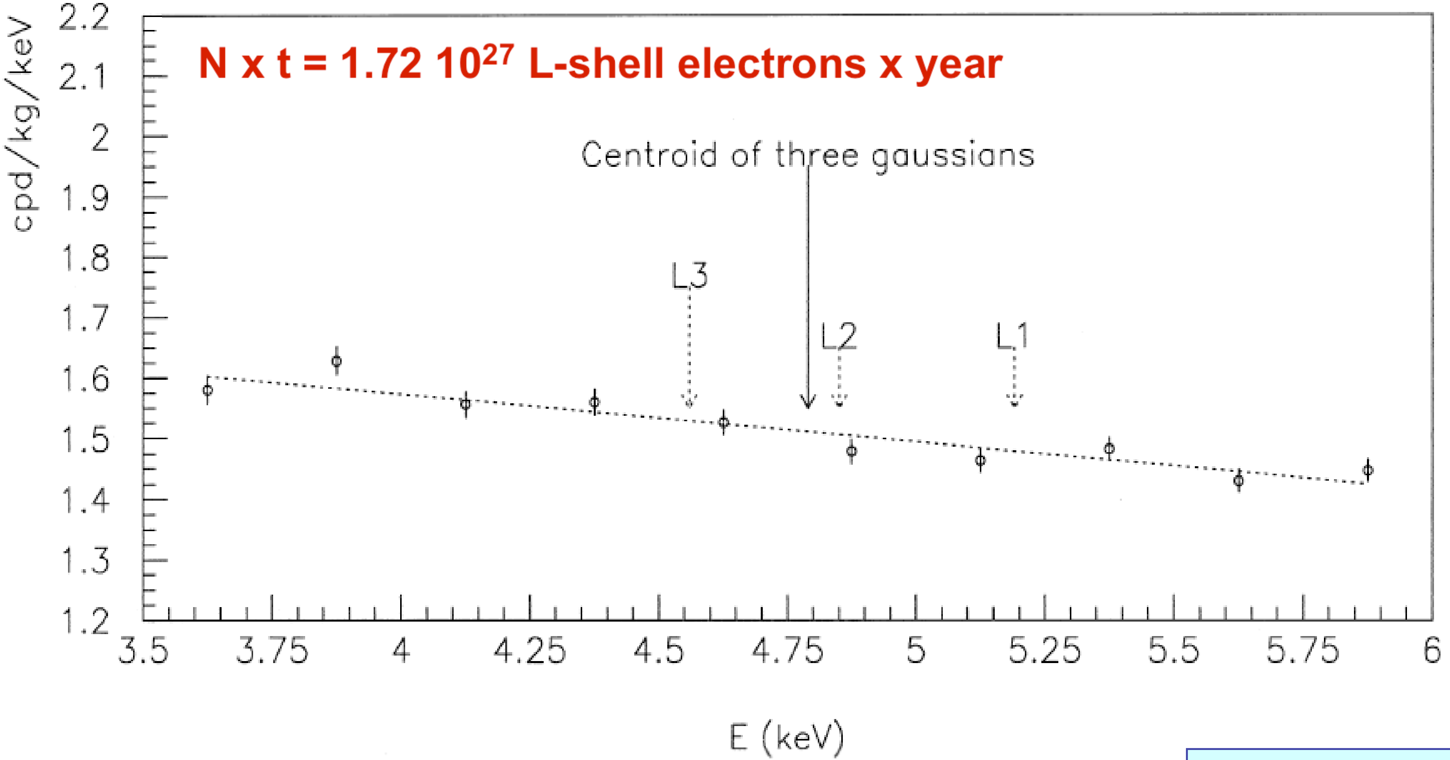


example of a PEP violating transition of Iodine electron to the full L-shell followed by the atomic shells rearrangement. The total released energy (x-ray + Auger electrons) is approximately equal to L-shell ionization potential (≈ 5 keV)

2) Search for non-paulian electronic transitions to L-shell

PLB 460 (1999) 236

Exposure: 19511 kg x day 2 annual cycles with low background DAMA/NaI



$$\tau = \frac{\varepsilon \cdot N \cdot t}{S}$$

ε detection efficiency for low energy x-rays and Auger electrons ≈ 100% in large NaI(Tl)

S < 413(715) 68%(90%) C.L.

$\tau > 4.2 \times 10^{24}$ y (68% C.L)

Considering that typical atomic transition lifetime are at timescale of ns

➡ **P < few 10^{-42} are explored**

Also limit on electron stability for the process: $e^- \rightarrow 3\nu$, majoron+ν or anything invisible.

The new DAMA/LIBRA set-up ~250 kg NaI(Tl)

(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

DAMA/LIBRA ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
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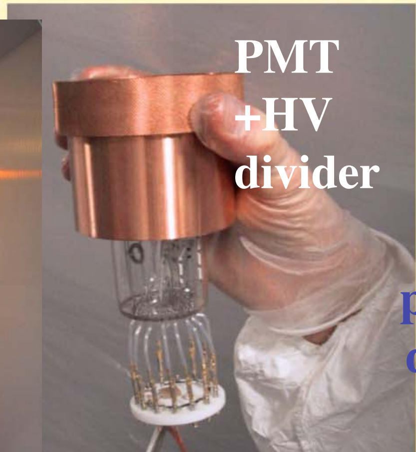
improving installation and environment



Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N_2

An example: the Cu etching

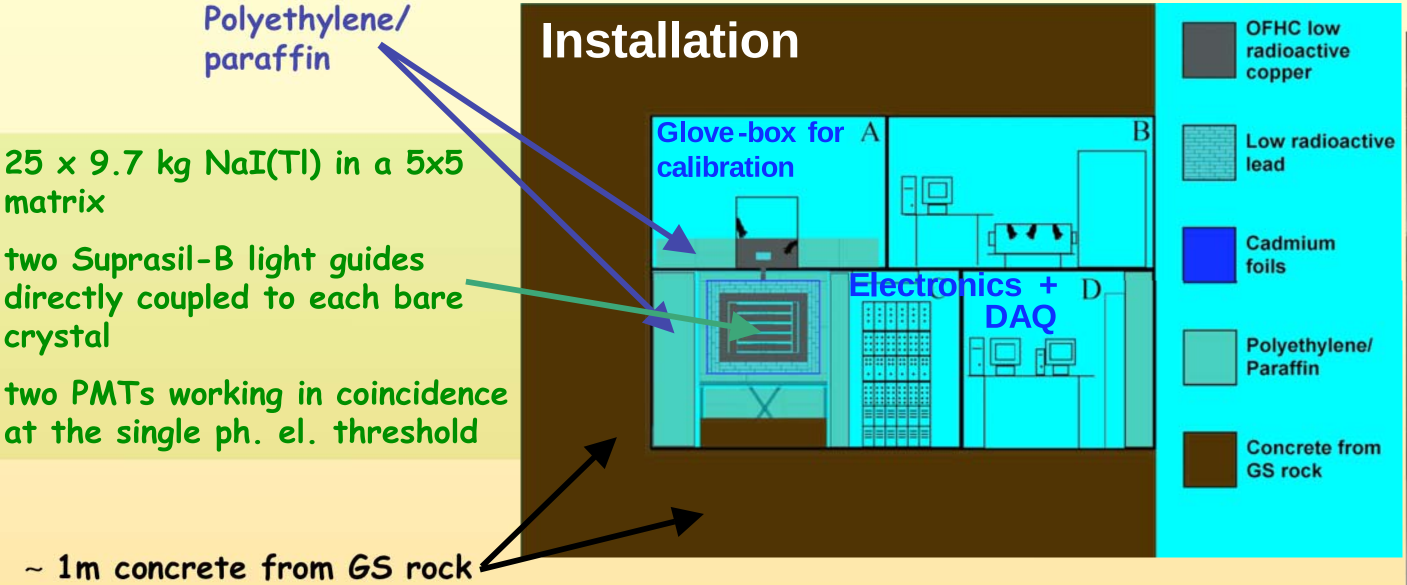
- The Cu etching was performed in a clean room following a devoted protocol:

vessel I: pre-washing of the brick in iper-pure waterc
vessel II: washing in 1.5l of HCl 3M super-pure
vessel III: first rinse with iper-pure water (bath)
vessel IV: second rinse with iper-pure water (current)
vessel V: washing in 1.5l of HCl 0.5M ultra-pure
vessel VI: first rinse with iper-pure water (bath)
vessel VII: second rinse with iper-pure water (current)
vessel VIII: third rinse with iper-pure water (current)
bricks dried with selected clean towels and HP N_2 flux
bricks sealed in two envelopes (one inside the other) flowed and filled with HP N_2

- Very clean materials (teflon and high purity OFHC copper, selected vessels and gloves) were used. Special tools were also used to help managing the bricks to minimize the contact with gloves.
- The residual contaminants in HCl are certified by the producer, in particular standard contaminants are quoted: 10 ppb for ^{nat}K and 1 ppb or U/Th for super-pure HCl and 100 ppt of ^{nat}K and 1 ppt for U/Th in case of ultra-pure HCl.
- For each brick the bath was changed and after each step the solution of the bath was analysed with ICP-MS technique.
- Residual contaminants were checked in order to optimize the choice of the materials (in particular for gloves) and the cleaning procedure. After cleaning, each brick was stored underground.

The DAMA/LIBRA set-up

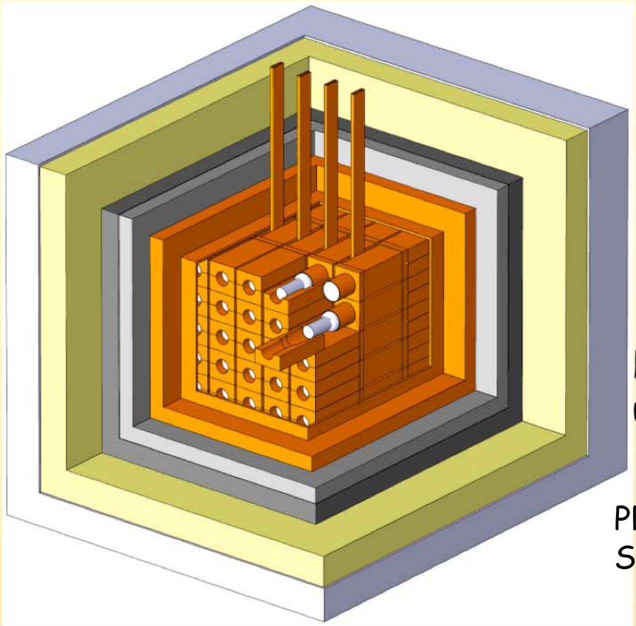
For details, radiopurity,performances, procedures, etc.
NIMA592(2008)297



- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer *TVS641A* (2chs per detector), 1 *Gsample/s*, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy

Shield from environmental radioactivity

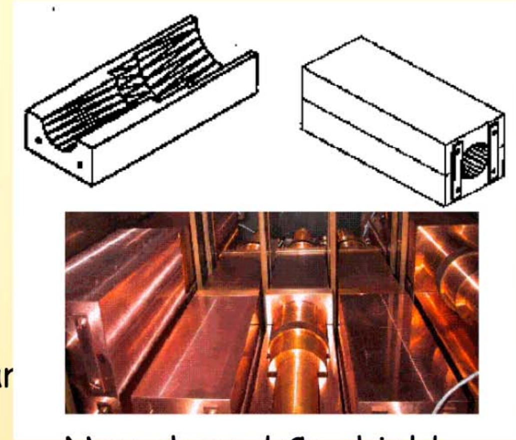


Heavy shield:

>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete (mostly outside the installation)

High radiopure materials, most underground since at least about 15 year

Pb and Cu etching and handling in clean room.
Storage underground in packed HP N_2 atmosphere



New shaped Cu shield surrounding light guides and PMTs

Three-level system to exclude Radon from the detectors:

- Walls and floor of the inner installation sealed in Supronyl (2×10^{-11} cm^2/s permeability).
- Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment
- Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment

Residual radioactivity in some components of the Cu box (95% C.L.)

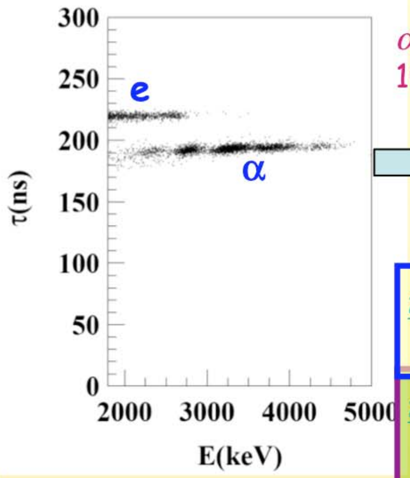
Materials	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
feedthroughs	—	< 1.6	< 1.8
Neoprene	—	< 54	< 89

Sensitivity limited by the method

Residual contaminants in some components of the passive shield (95% C.L.)

Materials	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
boliden Pb	< 8	< 0.03	< 0.06
boliden2 Pb	< 3.6	< 0.027	< 0.06
polish Pb	< 7.4	< 0.042	< 0.03
polyethylene	< 0.3	< 0.7	< 2
plexiglass	< 0.64	< 27.2	< 3.3

Some on residual contaminants in new NaI(Tl) detectors



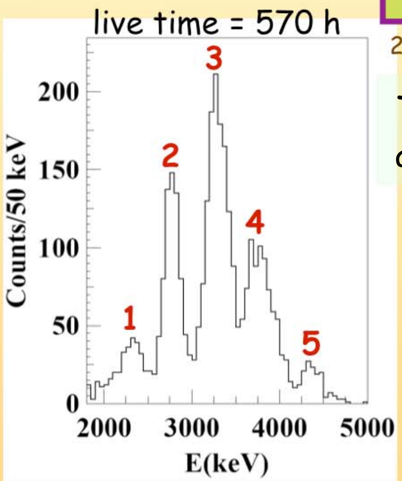
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{232}Th residual contamination: From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

^{238}U residual contamination: First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium $\Rightarrow$ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt



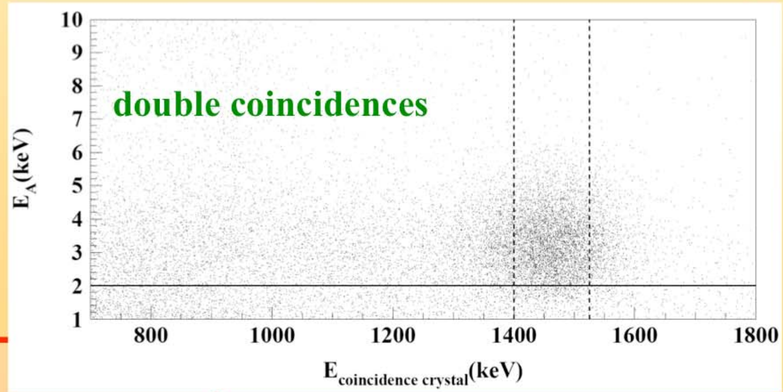
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

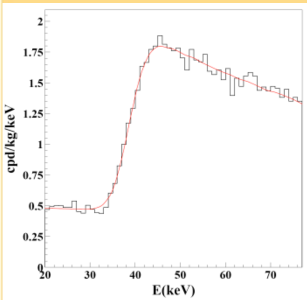
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

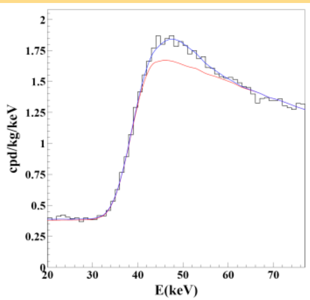
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb







^{129}I and ^{210}Pb

$^{129}I/^{nat}I \approx 1.7\times10^{-13}$ for all the new detectors

^{210}Pb in the new detectors: (5 – 30) μBq/kg.

No sizeable surface pollution by Radon daugthers, thanks to the new handling protocols

... more on NIMA592(2008)297

Infos about DAMA/LIBRA data taking

EPJC56(2008)333
NIMA592(2008)297

DAMA/LIBRA test runs: from March 2003 to September 2003

DAMA/LIBRA normal operation: from September 2003 to August 2004

High energy runs for TDs: September 2004
to allow internal α's identification
(approximative exposure ≈ 5000 kg × d)

DAMA/LIBRA normal operation: from October 2004

Data released here:

- four annual cycles: 0.53 ton × yr
- calibrations: acquired ≈ 44 M events from sources
- acceptance window eff: acquired ≈ 2 M events/keV

Period		Exposure (kg×day)	$\alpha - \beta^2$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	49377	0.541
Total		192824 ≃ 0.53 ton×yr	0.537

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

Two remarks:

•One PMT problems after 6 months. Detector out of trigger from Sep. 2003 to the 2008 update. Now again in operation.

•Residual cosmogenic ^{125}I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

DAMA/LIBRA is continuously running

Perspectives for PEP investigations with DAMA/LIBRA

1) Search for non-paulian nuclear processes

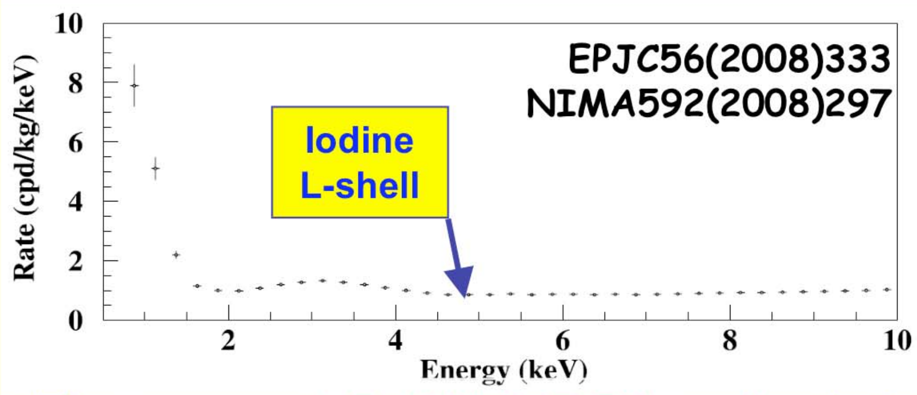
Radiopurities of the new DAMA/LIBRA detectors (and set up) are improved by respect to the case of DAMA/NaI.

Very low background expected also in the 10 - 36 MeV energy window.

Exposure larger than the previous 6.13×10^7 kg x s can be achieved in 4 days of dedicate high energy data taking.

WORK IN PROGRESS…

2) Search for non-paulian electronic transitions to L-shell



The present DAMA/LIBRA collected exposure 0.53 tons x year is a factor 10 larger than 19511 kg x day of previous PLB 460 (1999) 236.

The background in the ≈ 5 keV region has been improved of a factor ≈ 2.

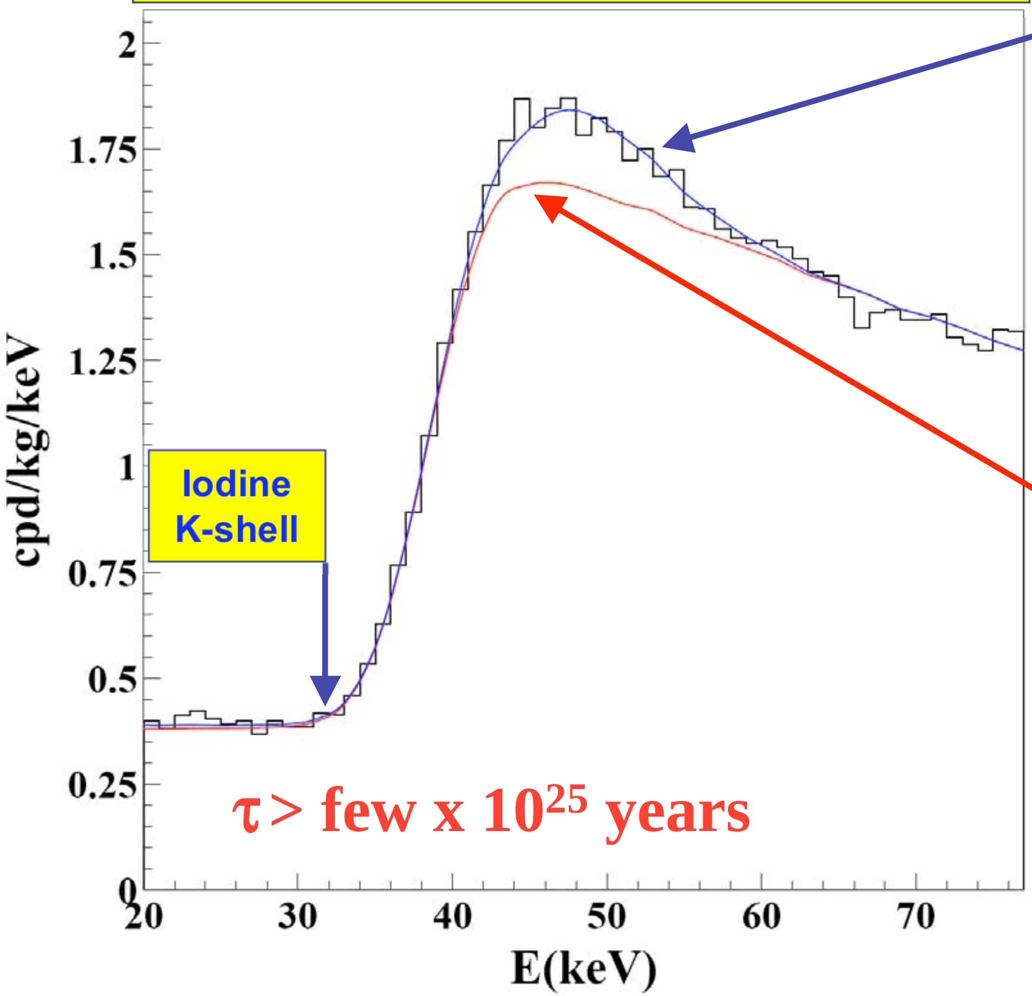
The DAMA/LIBRA sensitivity to electronic non-paulian transitions to a full L-shell in Iodine is at level of:

$\tau > 1.5 \times 10^{25}$ years at 68% C.L

Perspectives for PEP investigations with DAMA/LIBRA

3) Search for non-paulian electronic transitions to K-shell

example for a DAMA/LIBRA detector



^{210}Pb: a= (29±3) μBq/kg

No sizeable surface pollution by Radon daugthers, thanks to the new handling protocols ^{210}Pb in the new DAMA/LIBRA detectors typically ranges: (5 – 30) μBq/kg. ^{210}Pb peak is absent in most of the new DAMA/LIBRA detectors.

$^{129}I/^{nat}I = (1.7 \pm 0.1) \times 10^{-13}$

The amount of cosmogenic ^{129}I (β+γ) is at the same level (≈1.7×10^{-13}) for all the new detectors **(if used for dating the NaI powders ⇒ extracted from ore with an age of order of 50 Myr)**

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And more, a DAMA/LIBRA upgrade allowing 1 keV threshold is planned. Possible investigation of Sodium K-shell (≈1 keV). WORK IN PROGRESS...

CONCLUSIONS

Lifetimes at level of 10^{25} years both for non-paulian nuclear processes and for non-paulian electronic transitions can be investigated by DAMA/LIBRA.

Non-paulian mixing probability at level of $P<10^{-54}$ for nucleons and $P<10^{-42}$ for e^- can be explored.

If something in fundamental physics can be tested, then it absolutely must be tested (Okun)