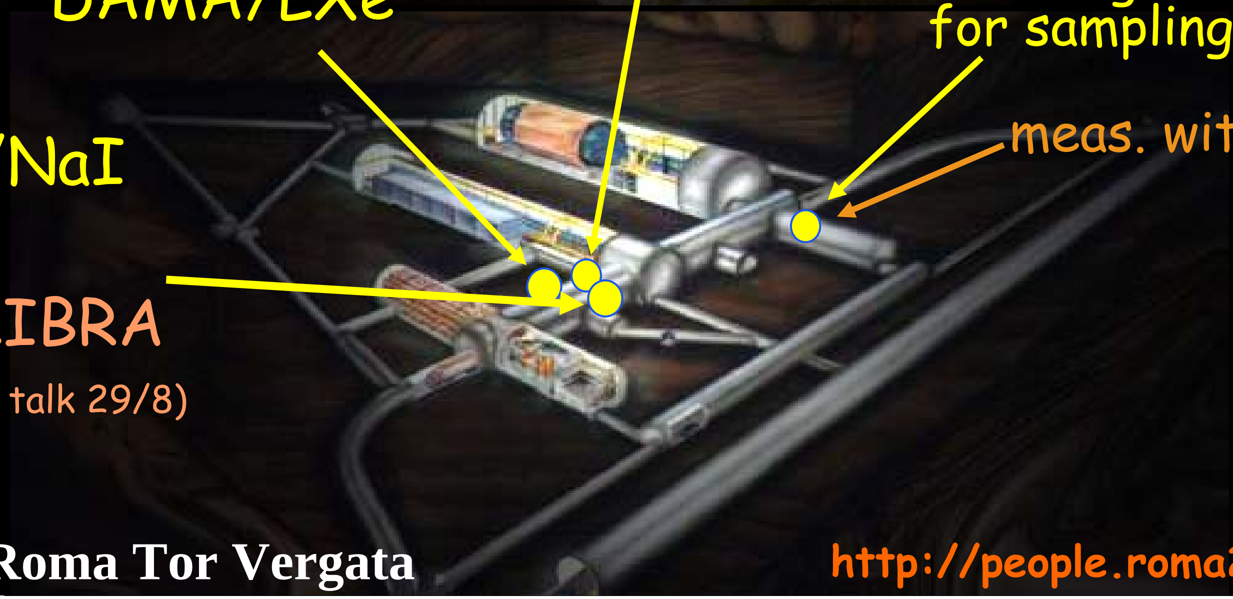
Roma2, Roma1, LNGS, IHEP/Beijing

+ in some small scale expts and by-products results: INR-Kiev
+ in the framework of MAE activity: IIT-Kharagpur
+ neutron measurements: ENEA- Frascati

13° Lomonosov Conf. Moscow 23 – 29 Aug. 2007

Search for rare processes at Gran Sasso



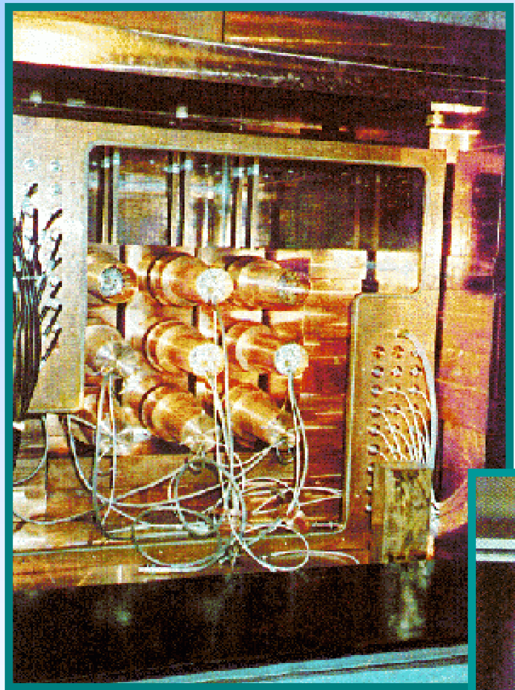
F. Nozzoli

INFN & Univ. Roma Tor Vergata

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

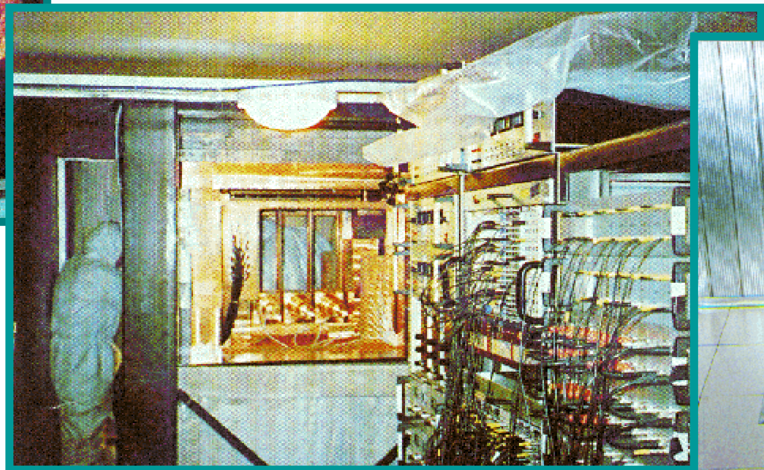
DAMA/NaI(Tl) ~100 kg

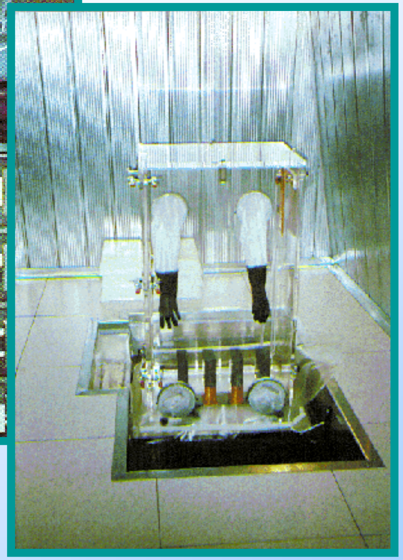
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127



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, EPJC18(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 + others in progress

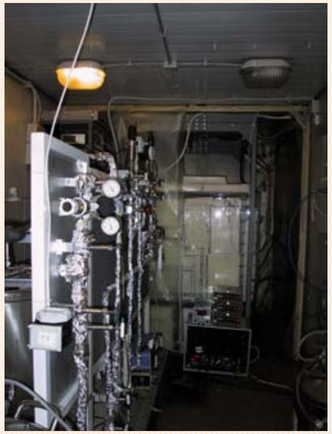
data taking completed on July 2002

total exposure collected in 7 annual cycles 107731 kg×d

DAMA/LXe

Unique low-background 6.5 kg LXe set-up operating as pure scintillator filled by Kr-free Xenon enriched either in ^{129}Xe (99.5%) or in ^{136}Xe (68.8%)

(NIMA482(2002)728)



DARK MATTER investigations ...

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by PSD PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering PLB387(1996)222, NJP2(2000)15.1
- Neutron calibrations PLB436(1998)379, EPJdirectC11(2001)1

... and other rare processes

- Electron decay into invisible channels AstroP5(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 $e^- \rightarrow \nu_e \gamma$ PRD61(2000)117301
- 2β decay in ^{134}Xe PLB527(2002)182
- 2β in ^{134}Xe & ^{136}Xe PLB546(2002)23
- CNC decay $^{136}Xe \rightarrow {}^{136}Cs$ Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe EPJA27 s01 (2006)35

- stand-by during all the period of the problems related to the use of "liquids" underground because of Borexino accident.
- restarted on May 2004, running till December 2004; then stopped again waiting for the necessary restoring of circulating water in the underground lab.
- Full revision + new chiller -> restart of data taking in 2007

DAMA/R&D

- Particle Dark Matter search with $CaF_2(Eu)$ NPB563(1999)97, AP7(1997)73
- 2β decay in ^{136}Ce and in ^{142}Ce Il N.Cim.A110(1997)189
- $2EC2\nu$ ^{40}Ca decay AstroP7(1999)73
- 2β decay in ^{46}Ca and in ^{40}Ca NPB563(1999)97
- $2\beta^+$ decay in ^{106}Cd AstroP10(1999)115

- 2β and β decay in ^{48}Ca NPA705(2002)29
- $2EC2\nu$ in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce NIMA498(2003)352
- $2\beta^+0\nu$ and $EC\beta^+0\nu$ decay in ^{130}Ba NIMA525(2004)535
- Cluster decay in $LaCl_3(Ce)$ NIMA555(2005)270
- CNC decay $^{139}La \rightarrow {}^{139}Ce$ UkrJP51(2006)1037
- Rare α decay of ^{151}Eu Nucl. Phys. A.798(2007)15
- 2β processes in ^{64}Zn Prep. ROM2F/2007/13

+several other results under analysis + data taking in progress + many other meas. scheduled

DAMA/Ge & LNGS Ge facility

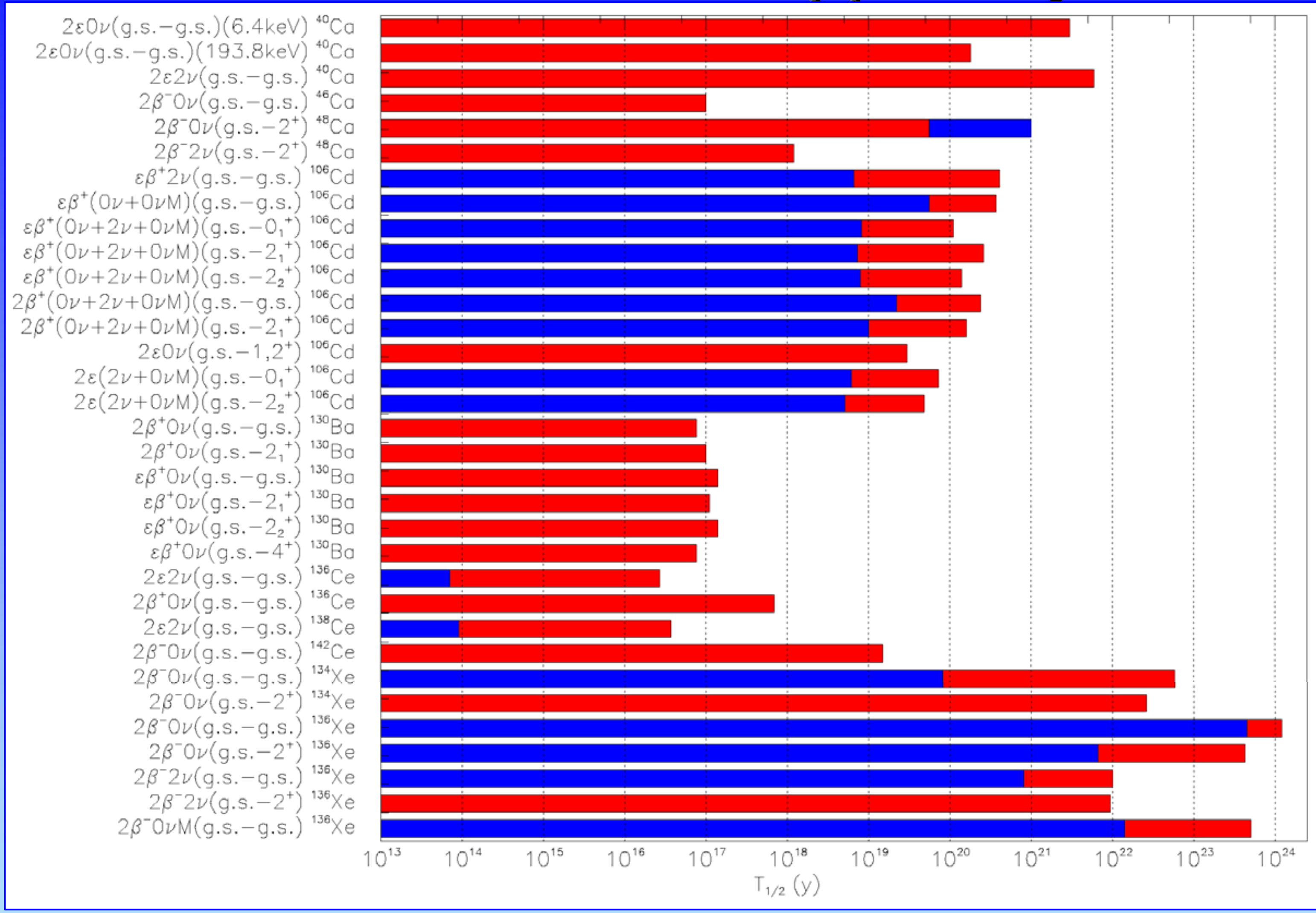
low background Ge detector operative in the Ge facility of LNGS mainly devoted to measurements and selections for:

- RD-I, RD-II and now RD-III on highly radiopure NaI(Tl) set-ups;
- 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 some double beta decay mode in progress in the 4π low-background HP Ge facility of LNGS (in the volume Nucl.Phys. and Atomic Energy,ed. INR-Kiev (2007), 479)

+ Many other meas. already scheduled

DAMA results on ββ decay



Experimental limits on $T_{1/2}$ obtained by DAMA (red) and by previous experiments (blue)

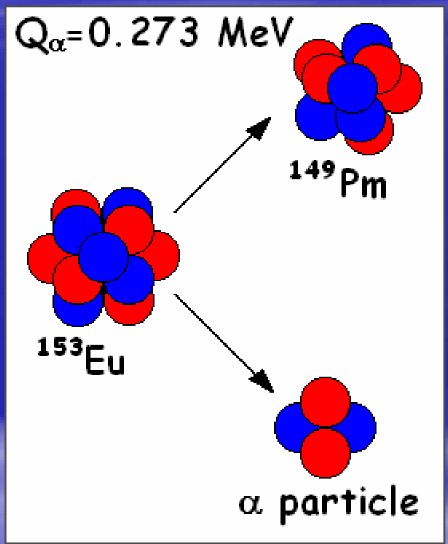
(all the limits are at 90% C.L. except for $2\beta^+0\nu$ in ^{136}Ce and $2\beta^-0\nu$ in ^{142}Ce - 68% C.L.)

Now in progress measurement on **2β2ν decay** in ^{100}Mo to the first excited 0^+_1 level of ^{100}Ru by using ~1 kg of Molybdenum enriched in ^{100}Mo at 99.5% inserted in a 4 HP Ge detector array

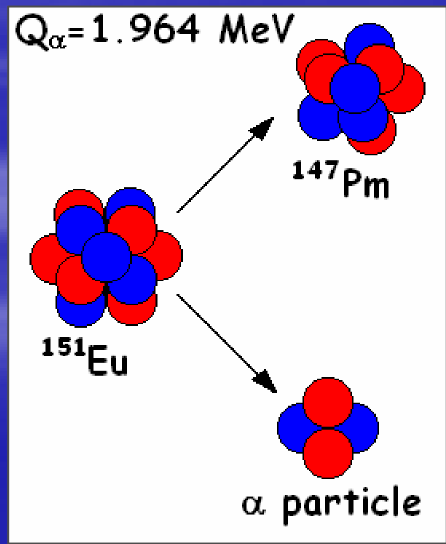
Search for α decay of natural Europium

NIM A 572 (2007) 734
Nucl.Phys.A798(2007)15

Both natural Europium isotopes, ^{151}Eu (natural abundance δ = 47.81(6)%) and ^{153}Eu (δ = 52.19(6)%) have a positive energy release respectively to α decay and, thus, they are potentially α radioactive.



The low Q_α for ^{153}Eu gives no hope for experimental observation of its decay due to the very big expected half-life.



However, for ^{151}Eu estimations of half-life give values on the level of 10^{18} y, and such a sensitivity can be reached with current experimental techniques.

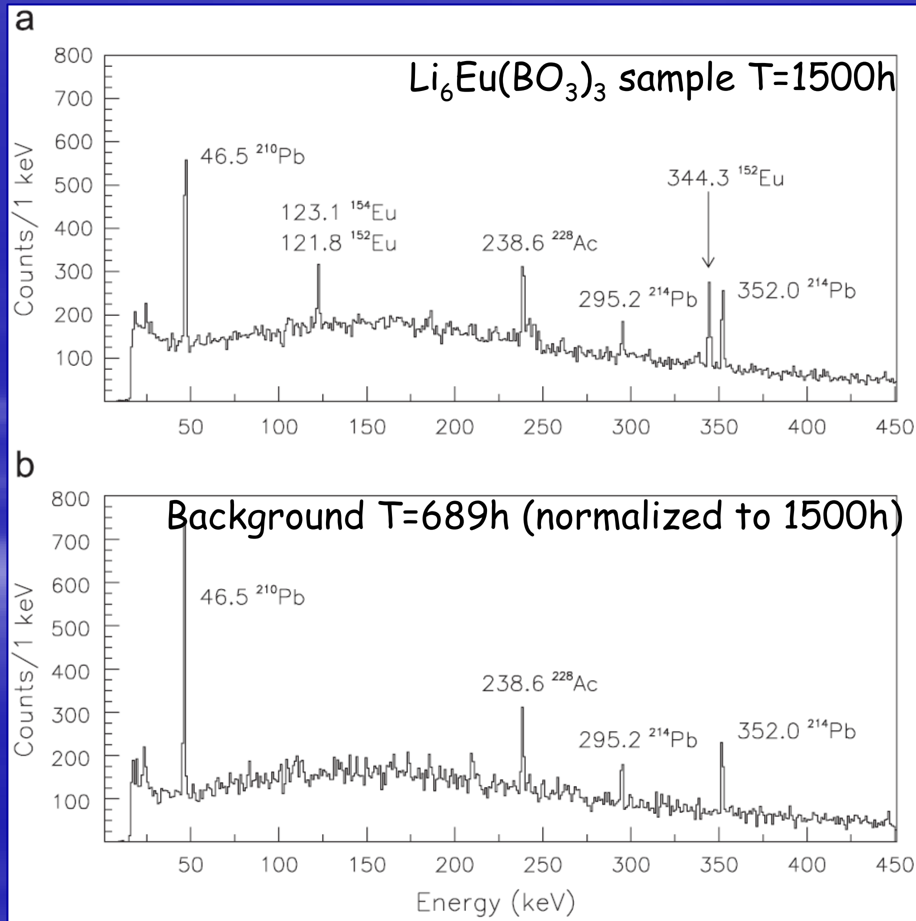
Search for α decays of Eu with a $Li_6Eu(BO_3)_3$ crystal

NIM A 572(2007)734

Greater content of Eu with respect to e.g. CaF_2(Eu), but poor scintillation properties and small size crystals

Exp set-up: $Li_6Eu(BO_3)_3$, 2.72 g, as external source + HP Ge detector (408 cm^3) in low-background set-up @ LNGS

Spectra measured with the HP Ge



Radioactive contamination in $Li_6Eu(BO_3)_3$:

Chain	Nuclide	Activity (Bq/kg)
^{232}Th	^{228}Ac	<0.20
	^{212}Pb	<0.25
	^{208}Tl	<0.13
^{238}U	^{214}Pb	<0.17
	^{214}Bi	<0.07
	^{40}K	<1.5
	^{60}Co	<0.026
	^{137}Cs	<0.081
	^{207}Bi	<0.009
	^{152}Eu	$=0.949(48)$
	^{154}Eu	$=0.212(35)$

Limits are given at 90% C.L.

^{152}Eu and ^{154}Eu contamination

Radioactive ^{152}Eu and ^{154}Eu nuclei were produced by neutron capture by ^{151}Eu and ^{153}Eu, respectively

Cross section for capture of thermal neutron: $\sigma_{151} = 5900 \pm 200$ b, $\sigma_{153} = 312 \pm 7$ b

Number of nuclei: $N_{151} = 7.78 \times 10^{20}$, $N_{153} = 8.49 \times 10^{20}$

Decay constant: $\lambda_{152} = \dfrac{\ln 2}{13.537}$ yr^{-1}, $\lambda_{154} = \dfrac{\ln 2}{8.593}$ yr^{-1}

Mass-spectrometric measurements showed that the Eu in the crystal was of normal composition: [47.9(3)% ^{151}Eu and 52.1(3)% ^{153}Eu]

$$\Rightarrow \frac{dN_d}{dt} = \phi \cdot \sigma_m \cdot N_m - \lambda_d \cdot N_d \quad \rightarrow \quad N_d(t) = \phi \cdot \sigma_m \cdot N_m \cdot \frac{\left(1 - e^{-\lambda_d t}\right)}{\lambda_d}$$

where $\begin{cases} m = 151\ (153) \\ d = 152\ (154) \end{cases}$

$$\frac{A_{152}}{A_{154}} = \frac{\lambda_{152} \cdot N_{152}(t)}{\lambda_{154} \cdot N_{154}(t)} = \frac{\sigma_{151} \cdot N_{151}}{\sigma_{153} \cdot N_{153}} \cdot \frac{\left(1 - e^{-\lambda_{152} t}\right)}{\left(1 - e^{-\lambda_{154} t}\right)}$$

$\Rightarrow$ for given N_m and σ_m: $11.00 < A_{152}/A_{154} < 17.33$

inconsistent with the measured ratio $A_{152}/A_{154} = 4.48 \pm 0.77$

Can be due to non-thermal neutrons flux from spontaneous fission of Th and U, and from (α,n) reactions in the monazite ores (which is a commercial source for both Eu and Th elements).

Alpha decays of Eu to Pm

NIM A 572(2007)734

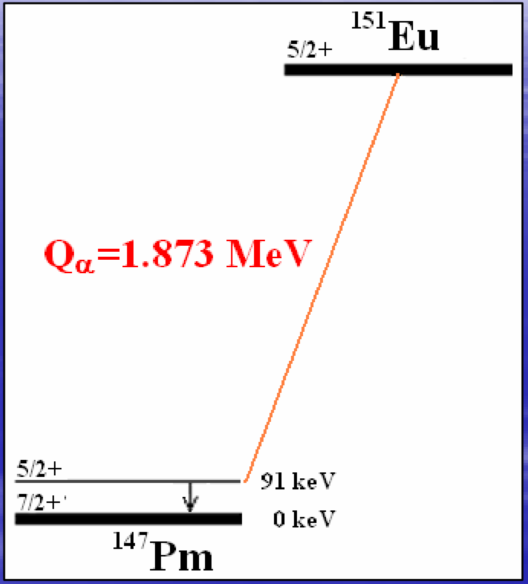
^{151}Eu (g.s.) → ^{147}Pm $(5/2^+)$

No evidence for 91.1 keV γ in the spectrum:

$$\lim T_{1/2} = (\ln 2 \cdot \varepsilon \cdot y \cdot N_{151} \cdot T) / \lim S$$

ε=2.8%; y (yield)=0.327

1. One σ approach: $T_{1/2} > 4.0 \times 10^{16}$ yr (68% C.L.)
2. Fit by the sum of the background model (straight line) + Gaussian peak ⇒ S = 12±14 counts



$$T_{1/2} > 2.4 \times 10^{16} \text{ yr} \quad (90\% \text{ C.L.})$$

^{153}Eu (g.s.) → ^{149}Pm (g.s.)

– very low Q_α=274 keV –

No evidence for 286 keV γ emitted in the β decay of ^{149}Pm (yield=3.1%, ε=11.0%)

$$T_{1/2} > 1.1 \times 10^{16} \text{ yr} \quad (90\% \text{ C.L.})$$

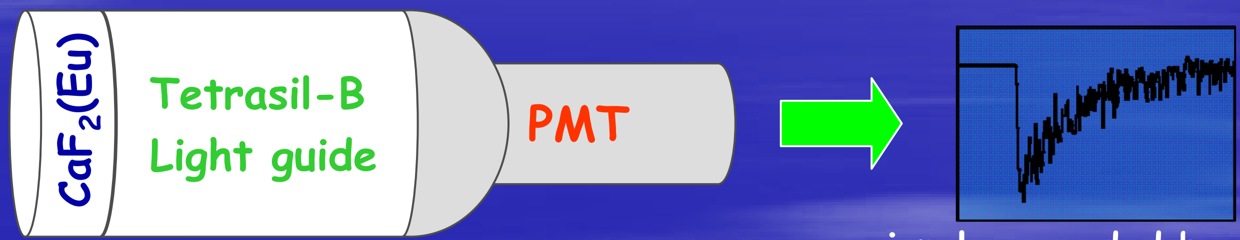
Search for α decays of Eu with a CaF_2(Eu) crystal

Nucl.Phys.A798(2007)15

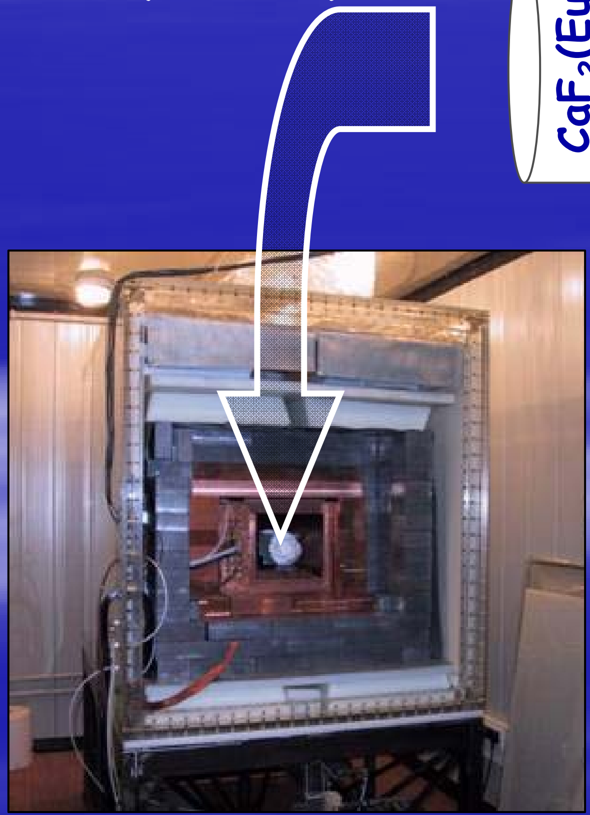
- Low background CaF_2(Eu) scintillator, 3" diameter, 1" in length → 370 g mass
- Pure quartz light guide (TETRASIL-B), 10 cm long to
- Low background photomultiplier (PMT) EMI9265-B53/FL.

(Scintillation crystal and light guide wrapped by PTFE reflection tape)

Eu concentration:
ICP-MS (0.4 ± 0.1)%



signals recorded by a 160 MSa/s Transient Digitizer over a 3125 ns time window



DAMA/R&D set-up at LNGS

Low radioactive Cu box flushed with HP N_2

Passive shield
- 10 cm of high purity Cu
- 15 cm of low radioactive lead
- 1.5 mm of cadmium and
- 4 to 10 cm of polyethylene/paraffin

The whole shield closed inside a Plexiglas box also flushed with HP N_2

Response to γ quanta and α particles

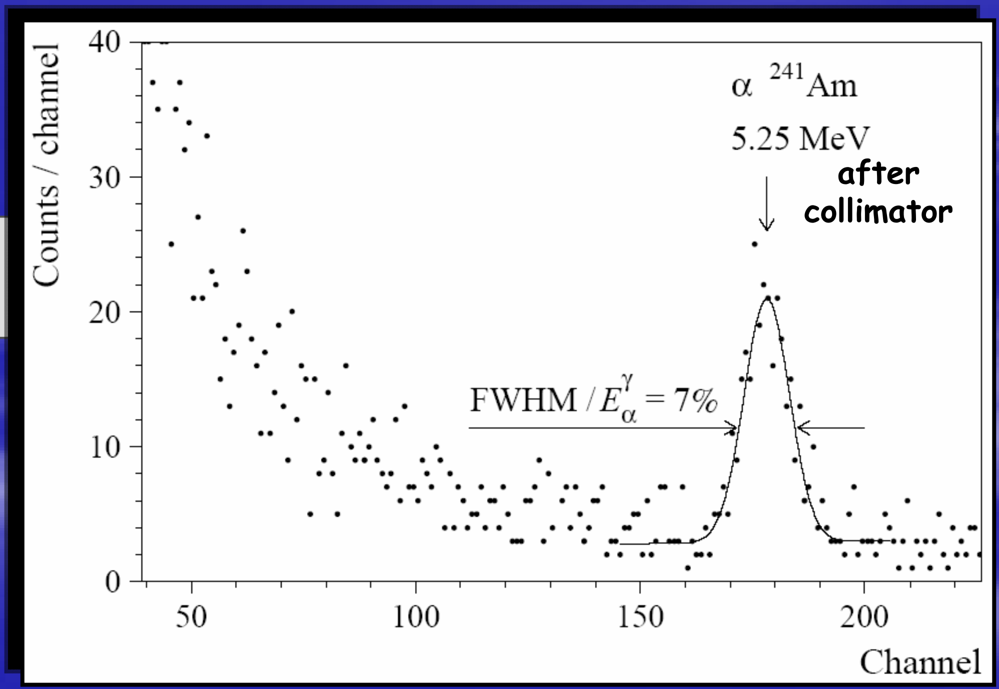
Nucl.Phys.A798(2007)15

Energy scale and resolution for γ quanta measured with ^{22}Na, ^{133}Ba, ^{137}Cs, ^{228}Th and ^{241}Am sources.

$$\mathrm{FWHM}_\gamma(\mathrm{keV}) = \sqrt{3.7(4)\cdot E_\gamma[\mathrm{keV}]}$$

(e.g.: 28% @ 60 keV; 11.4% @ 356 keV and 7.5% @ 662 keV)

Response to α particles studied with a collimated ^{241}Am α source.

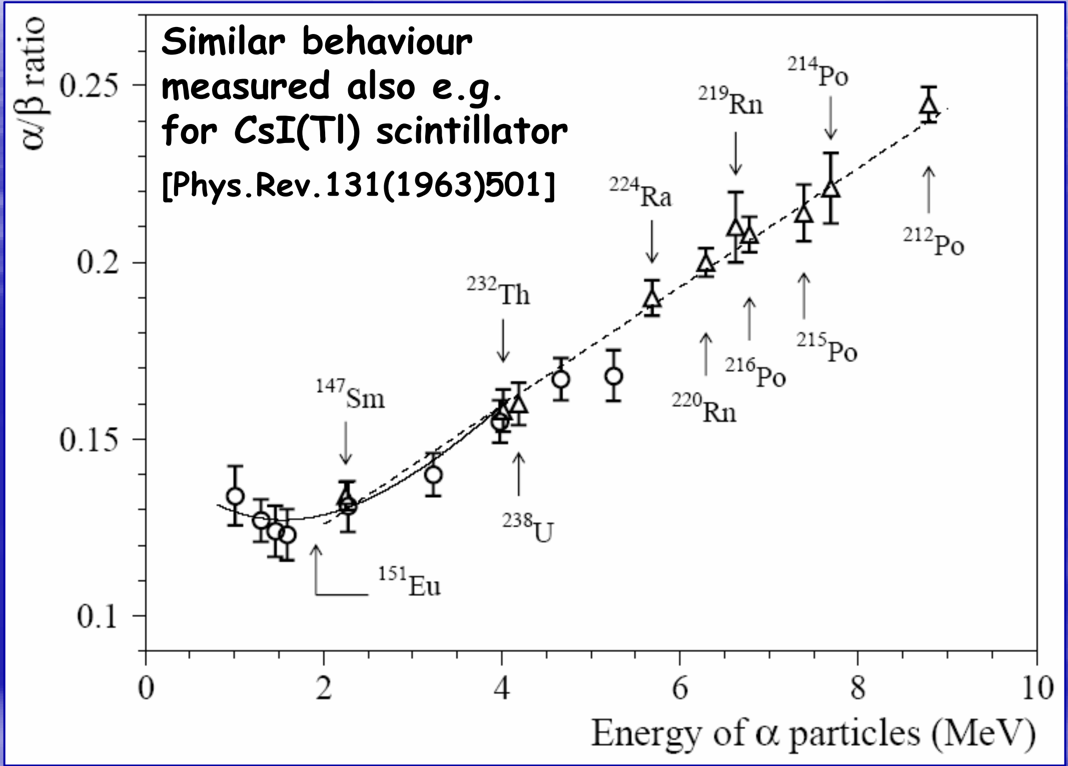


Specific α's energies in the interval 1.00–5.25 MeV obtained with a set of calibrated absorbers (mylar 0.65 mg/cm^2,air).

$$\mathrm{FWHM}_\alpha / E_\alpha^\gamma = 7\%$$

Energy dependence of the α/β ratio

Nucl.Phys.A798(2007)15



o Points measured with ^{241}Am source (1.00, 1.30, 1.45, 1.59, 2.27, 3.23, 3.98, 4.66, 5.25 MeV)

Δ Peaks identified from the measured background

If E_α> 2 MeV (linear behaviour):

$$\alpha / \beta = 0.092(4) + 0.0168(7) \cdot E_\alpha [\mathrm{MeV}]$$

Non-linear behaviour near 2 MeV ⇒ fit by polynomial function (continuous line)

α/β = 0.128(19) at the energy of ^{151}Eu α particles

⇒ ^{151}Eu α peak expected at 245(36) keV (in gamma scale)

Pulse-shape discrimination between α and γ(β)

Nucl.Phys.A798(2007)15

Shape Indicator (*SI*): numerical parameter of $CaF_2(Eu)$ signal

SI distribution for:
α particles (≈4 MeV) and
γ quanta (≈ 0.6 MeV)

For each pulse:

$$SI = \frac{\sum_k f(t_k)P(t_k)}{\sum_k f(t_k)}$$

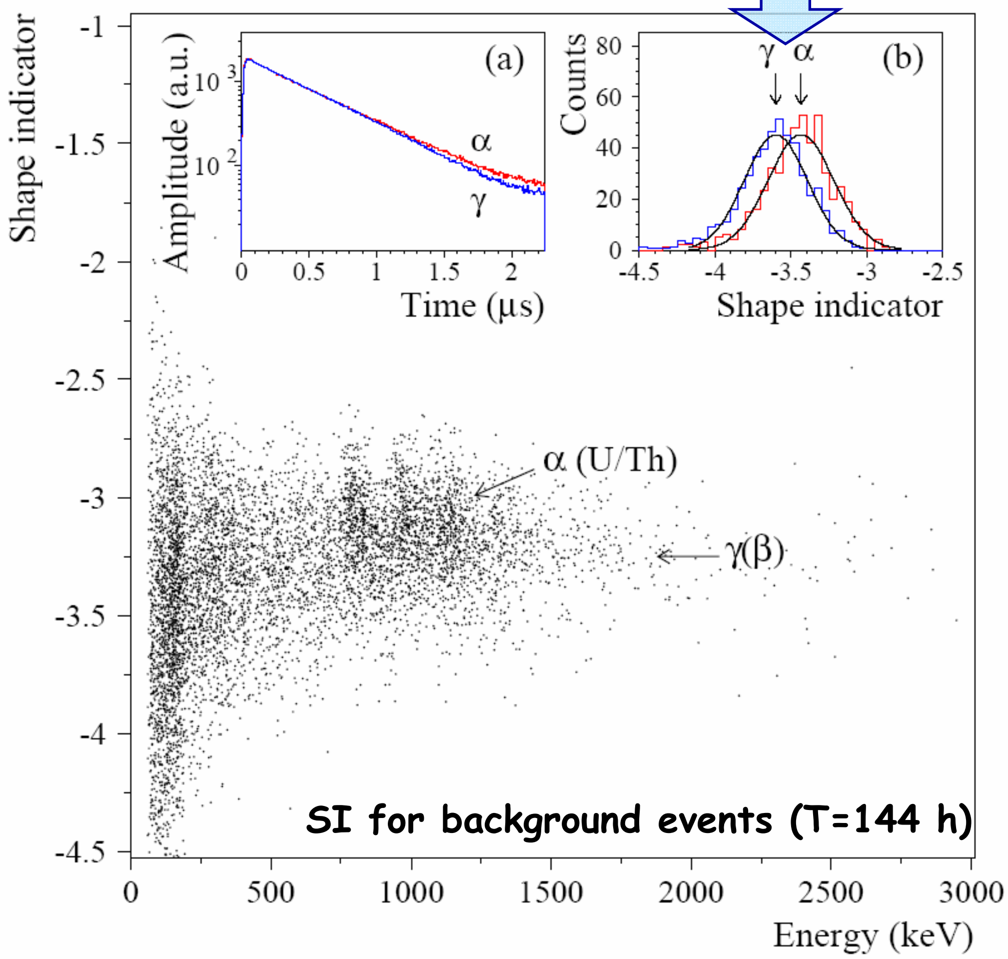
[0,2.25] μs

$$P(t) = \frac{f_\alpha(t) - f_\beta(t)}{f_\alpha(t) + f_\beta(t)}$$

$f(t_k)$ = digitized amplitude of signal

$P(t) = \{f_\alpha(t) - f_\gamma(t)\}/\{f_\alpha(t) + f_\gamma(t)\}$
(weight function)

$f_\alpha(t)$, $f_\gamma(t)$ = reference pulse shapes

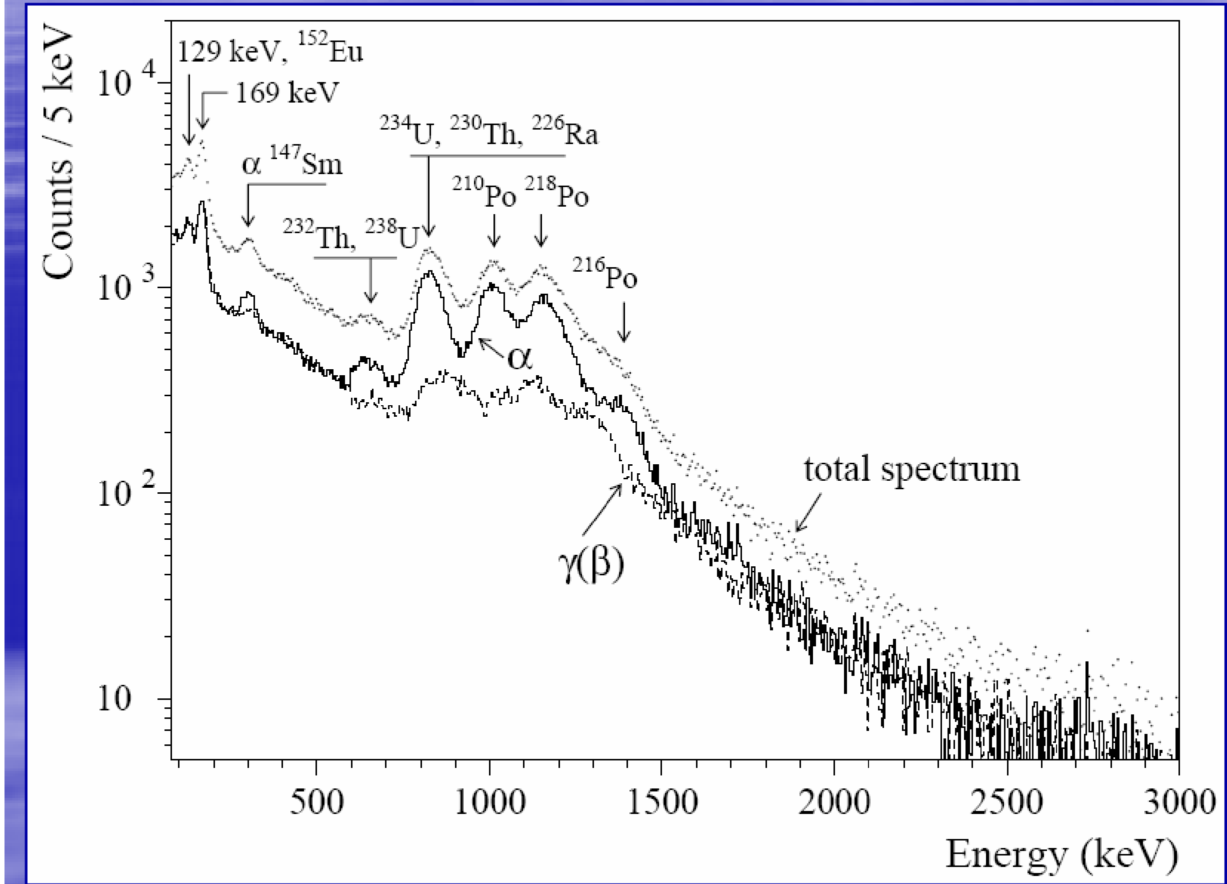


SI for background events (T=144 h)

Despite rather low discrimination, SI allows to check the nature of background

Measured energy spectrum (7426 h)

Nucl.Phys.A798(2007)15



<u>Data separated in 2 parts:</u>

γ(β): with condition $SI < SI_\gamma$
(50% of γ(β) events)

α: with condition $SI > SI_\gamma$.
(50% of γ(β) events but larger number of α)

Visible difference between the spectra

Pulse-shape discrimination useful to identify α active nuclides in the crystal.

Background identification: Time-amplitude analysis

Nucl.Phys.A798(2007)15

Arrival time and energy of each event used for the selection of fast decay chains in ^{232}Th and ^{235}U families.

T = 7426 h

^{232}Th family

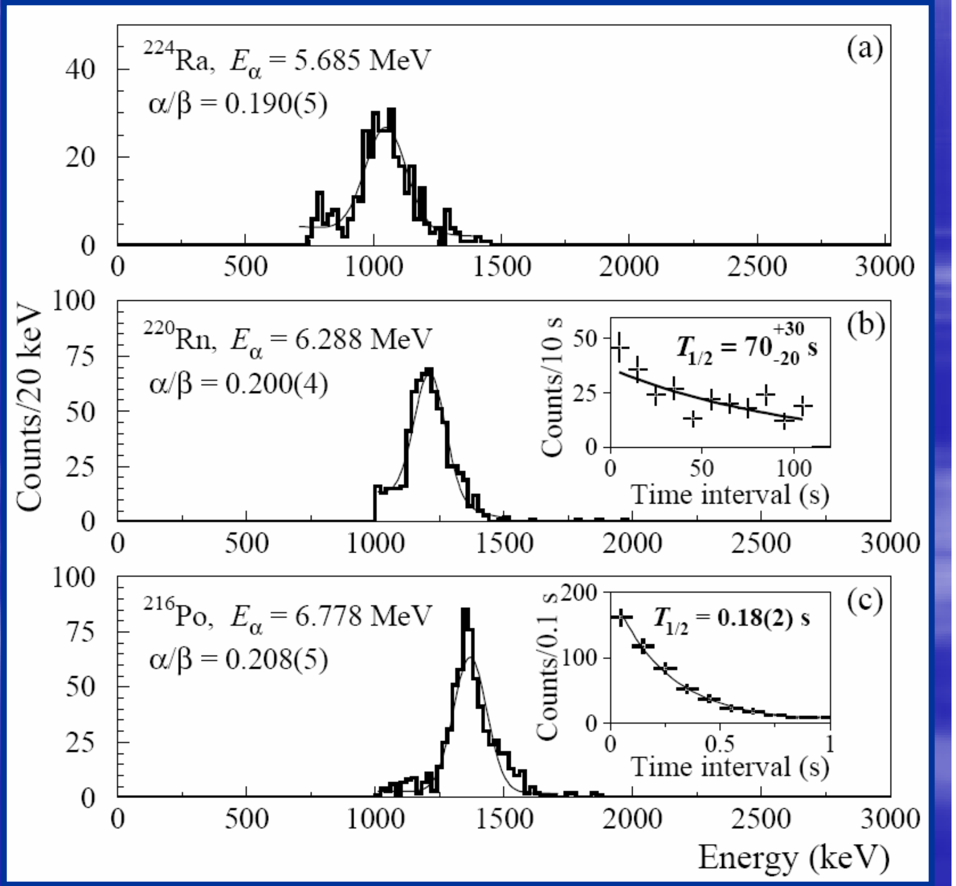
^{224}Ra (Q_α=5.789 MeV, $T_{1/2}$=3.66 d)

→ ^{220}Rn (Q_α=6.405 MeV, $T_{1/2}$=55.6 s)

→ ^{216}Po (Q_α=6.907 MeV, $T_{1/2}$=0.145 s)

→ ^{212}Pb

^{228}Th activity = 0.134(17) mBq/kg



^{235}U family

^{223}Ra (Q_α=5.98 MeV, $T_{1/2}$=11.44 d)

→ ^{219}Rn (Q_α=6.95 MeV, $T_{1/2}$=3.96 s)

→ ^{215}Po (Q_α=7.526 MeV, $T_{1/2}$=1.78 ms)

→ ^{211}Pb

^{227}Ac activity = 0.011(7) mBq/kg

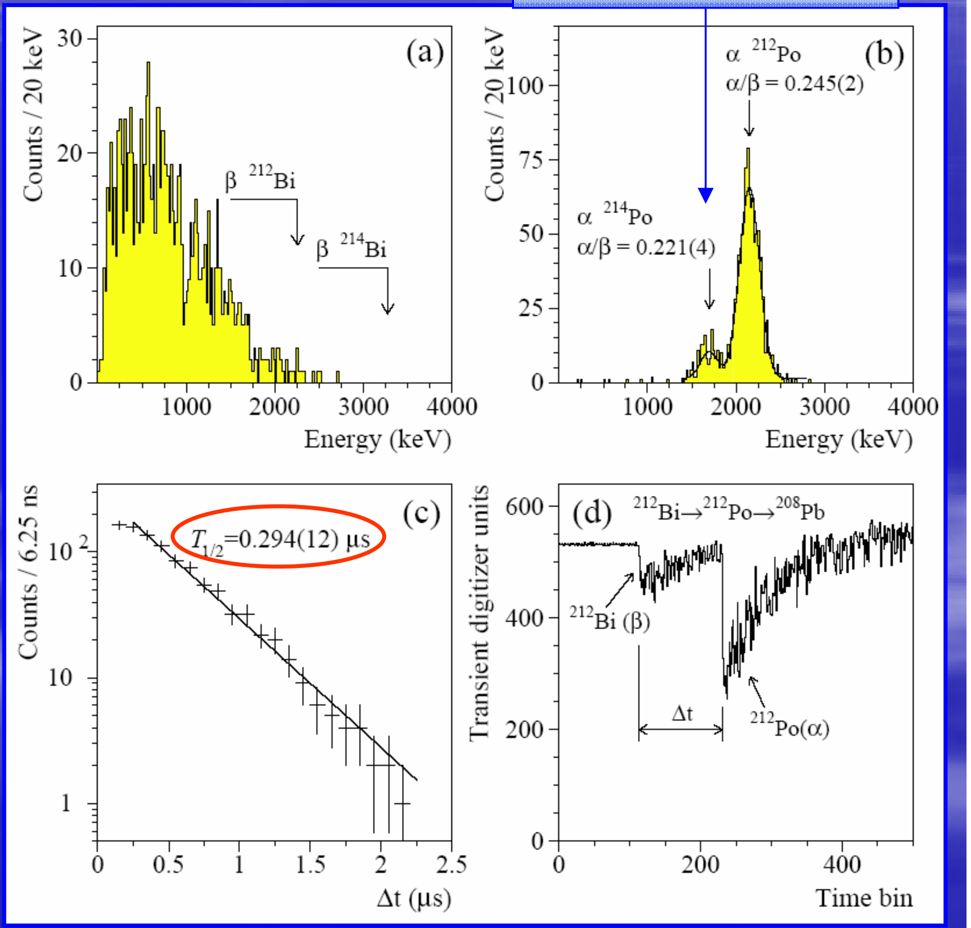
Background identification: Bi-Po events

Nucl.Phys.A798(2007)15

Selection of double pulses produced by very fast decay chains (the so called Bi-Po events)

T = 7426 h

depressed by a factor ≈ 110 because of the used TD time window



^{232}Th family

^{212}Bi (Q_β=2.254 MeV)

→ ^{212}Po (Q_α=8.954 MeV, $T_{1/2}$=0.299 μs)

→ ^{208}Pb

^{228}Th activity = 0.124(5) mBq/kg

(in agreement with time-amplitude analysis)

^{238}U family

^{214}Bi (Q_β=3.272 MeV)

→ ^{214}Po (Q_α=7.833 MeV, $T_{1/2}$=164 μs)

→ ^{210}Pb

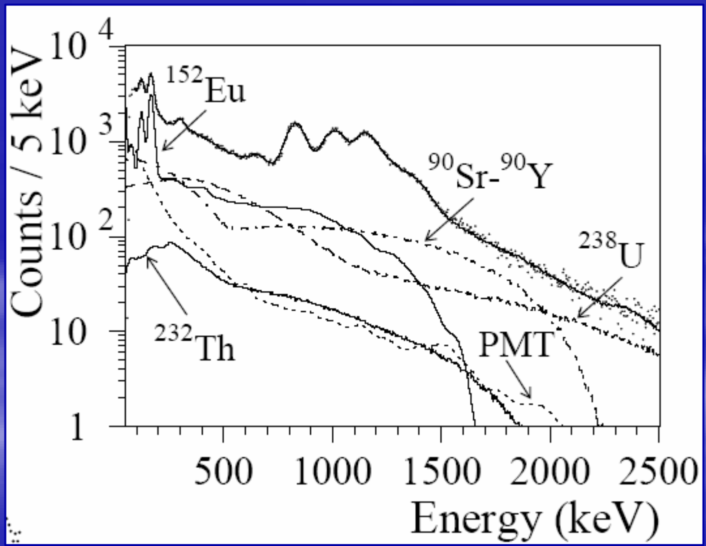
^{226}Ra activity = 1.3(2) mBq/kg

Radioactive contamination of the CaF_2(Eu)

Nucl.Phys.A798(2007)15

Activities of α active nuclides in CaF2(Eu) estimated by analysis of identified α peaks

Presence in the crystal of β active isotopes (U/Th families, ^{40}K, ^{60}Co, ^{90}Sr-^{90}Y, ^{137}Cs, ^{154}Eu) and external γ rays simulated with GEANT4



At low energy the background is caused mainly by β decay of ^{152}Eu

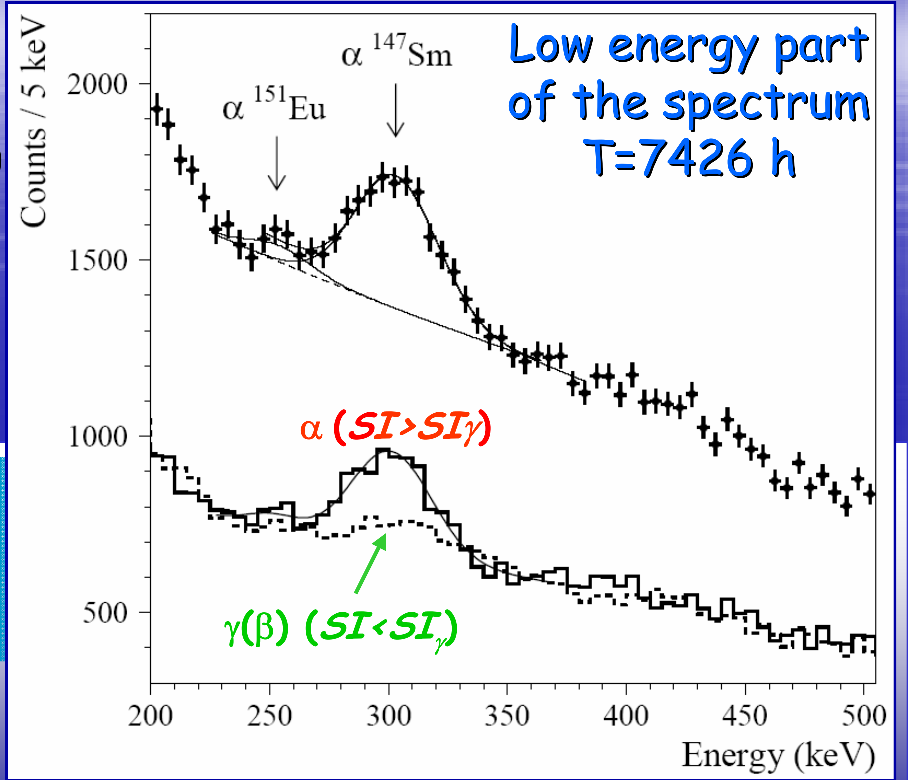
Chain	Nuclide	Activity mBq/kg
^{232}Th	^{232}Th	0.05(1)
	^{228}Ra	≤ 0.6
	^{228}Th	0.13(2)
^{235}U	^{227}Ac	0.011(7)
^{238}U	^{238}U	0.06(1)
	^{226}Ra	1.3(2)
	^{210}Po	0.9(2)
Total U/Th α activity		8(2)
	^{40}K	≤ 7
	^{60}Co	≤ 3
	^{90}Sr$-^{90}$Y	≤ 4
	^{137}Cs	≤ 0.3
	^{147}Sm	0.34(4)
	^{152}Eu	10(2)
	^{154}Eu	≤ 0.5

α decay ^{151}Eu → ^{147}Pm

Nucl.Phys.A798(2007)15

Peculiarity on the left of the ^{147}Sm peak can be attributed to the α decay of ^{151}Eu (expected peak at 1.912 MeV⇒245±36 keV)

Spectrum fitted by simple model:
2 Gaussian peaks (α decay of ^{151}Eu and ^{147}Sm)
+ exponential function (background)



1. Fit of the total spectrum [225,365 keV]:
   S = (302 ± 232) counts (χ^2/ndf=0.42)
   E_{peak} = (255±7) keV -> (1.98±0.04) MeV
   $T_{1/2} = 5.4^{+11.4}_{-2.4}(stat) \pm 1.4(syst) \times 10^{18}$ y

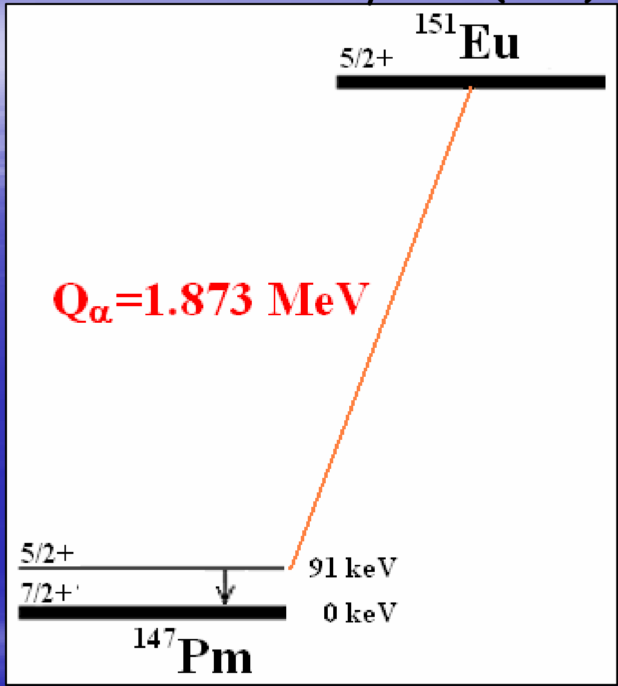
2. Fit of the α spectrum (efficiency=68% from ^{147}Sm peak) in [225,365 keV] :
   S = (374 ± 329) counts ⟶ $T_{1/2} = 4.4^{+11.3}_{-2.1}(stat) \times 10^{18}$ y
   E_{peak} = (253±7) keV -> (1.96±0.03) MeV

^{151}Eu α decay: $T_{1/2} = 5^{+11}_{-3} \times 10^{18}$ y

… or in a conservative approach: $T_{1/2} \geq 1.7 \times 10^{18}$ y (68% C.L.)

α decay of ^{151}Eu to the first excited level of ^{147}Pm

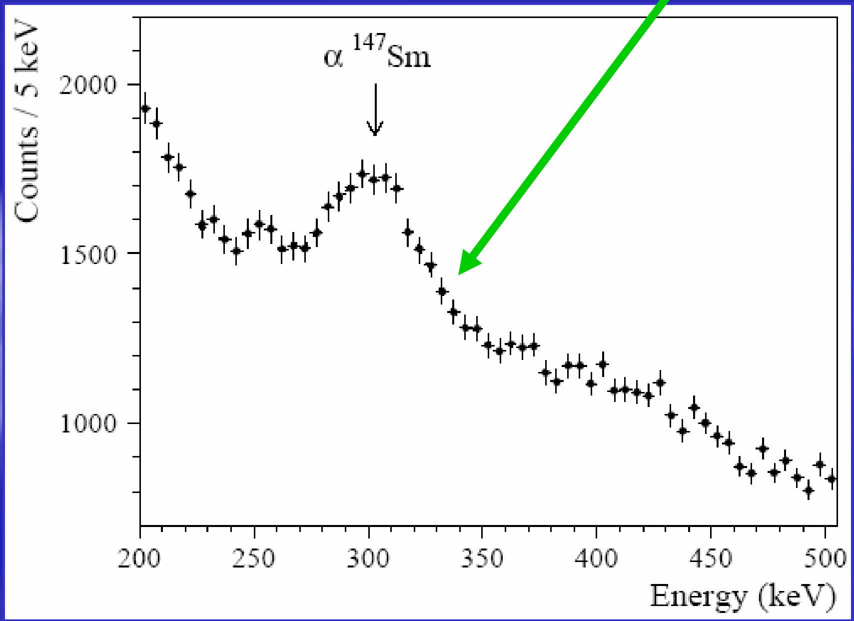
Nucl.Phys.A798(2007)15



E_α = 1.823 MeV corresponds to energy 234 keV in the γ scale of the CaF2(Eu) detector.

Subsequent 91 keV deexcitation energy (γ, 33%, or X rays/Auger electrons, 67%) effectively absorbed

$\Rightarrow$ Expected peak at (325±33) keV



Fit model:

2 Gaussian peaks (α decay of ^{151}Eu and ^{147}Sm)

+ exponential function (background)

No evidence:

$$T_{1/2}(g.s. \rightarrow 5/2^+) \geq 6\times10^{17}\ \text{yr}$$

(68% C.L.)

Implications

Nucl.Phys.A798(2007)15

Presence of Promethium in the Earth crust

- It is one of the rarest elements (all isotopes unstable with $T_{1/2}$<18 yr)
- Present only as temporal product (predominantly from ^{238}U spontaneous fission)
- It is possible to calculate about 560 g of natural Pm in the Earth crust

Observed α decay of ^{151}Eu opens additional source of natural Pm.

Taking into account the abundance of Europium in the crust ($2\times10^{-4}\%$)

$\Rightarrow$ additional 12^{+17}_{-8} g of natural Pm born by ^{151}Eu

Comparison with theory

[1] B. Buck et al., J. Phys. G 17 (1991) 1223; 18 (1992) 143.
[2] D.N. Poenaru, M. Ivascu, J. Physique 44 (1983) 791.
[3] G. Royer, J. Phys. G 26 (2000) 1149.
[4] M. Fujiwara et al., J. Phys. G 28 (2002) 643.
[5] D.N. Poenaru et al., Phys. Rev. C 32 (1985) 2198.

Populated level	Theoretical $T_{1/2}$, yr [1]	[2]	[3]	[4]	[5]	Experimental $T_{1/2}$, yr
ground state	3.0×10^{17}	3.6×10^{18}	6.3×10^{17}	5.9×10^{17}	1.6×10^{18}	$5^{+11}_{-3}\times10^{18}$
$5/2^+$, 91 keV	7.7×10^{18}	1.0×10^{20}	1.5×10^{19}	1.7×10^{19}	–	$\geq6\times10^{17}$

G.S.: Measured $T_{1/2}$ is in agreement with theoretical value [2] and [5].

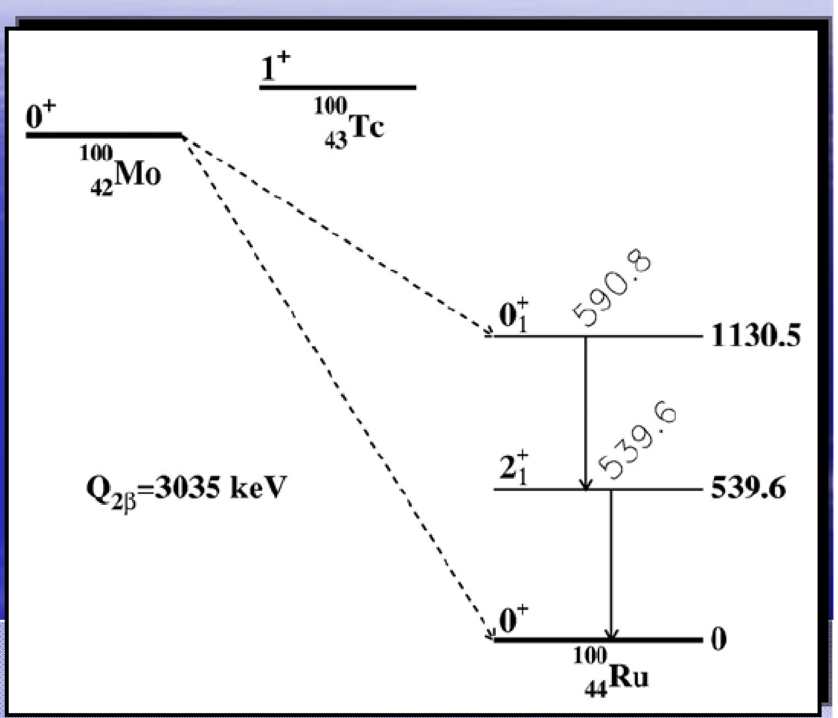
Search for $2\beta2\nu(0^+ \rightarrow 0^+_1)$ of ^{100}Mo

in the volume Nucl.Phys. and Atomic Energy, ed. INR-Kiev (2007), 479

For two nuclides, ^{100}Mo and ^{150}Nd, $2\beta2\nu$ decay has been observed also for transition to the first excited 0^+_1 levels of daughter nuclei

Transition (g.s.→g.s.) of ^{100}Mo has been observed in six experiments:

$T_{1/2} = 7.7 \pm 0.5 \times 10^{18}$ yr [JETP Letters 80(2004)377]



Transition of ^{100}Mo to 0^+_1 level of ^{100}Ru has been positively identified in four experiments by Barabash et al.:

$T_{1/2} = 6.1^{+1.8}_{-1.1} \times 10^{20}$ y [Phys.Lett.B 345(1995)408]
$T_{1/2} = 9.3^{+2.8}_{-1.7} \times 10^{20}$ y [Phys.At.Nucl. 62(1999)2039]
$T_{1/2} = 5.9^{+1.8}_{-1.3} \times 10^{20}$ y [Phys.Rev.Lett. 86(2001)3510]
$T_{1/2} = 5.7^{+2.1}_{-1.7} \times 10^{20}$ y [Nucl.Phys.A 781(2007)209]

in agreement among themselves, but not with the old NEMO data:
$T_{1/2} > 1.2 \times 10^{21}$ y at 90% C.L. [Phys.Lett.B 275(1992)506]

Experimental set-up

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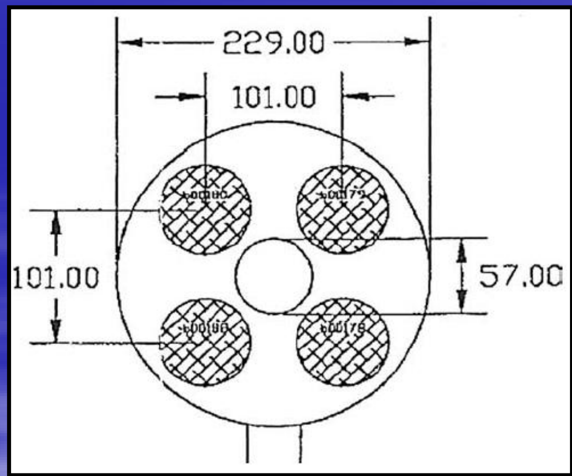
ARMONIA Collaboration: meAsuReMent of twO-NeutrIno ββ decAy of ^{100}Mo to the first excited 0^+ level of ^{100}Ru

Aim of the experiment: to confirm previous positive results or to set more stringent limit on the probability of the process

Data collected at LNGS in low-background set-up with 4 HP Ge detectors (each of ~225 cm^3).

Mo sample:

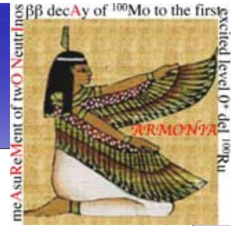
1009 g of Mo (metallic powder) enriched by ^{100}Mo at 99.5%, compressed to ~6 g/cm^3 to fill fully the well in the HP Ge set-up; some amount also above the detectors.



Germanium detectors parameters

	Detectors			
	ge178	ge179	ge180	ge188
Volume (cm^3)	225.2	225.0	225.0	220.7
Endcap and holder material	Electrolytical copper			
Energy resolution (FWHM) at 1332 keV	2.1	2.0	2.0	2.0

Measurements and preliminary results



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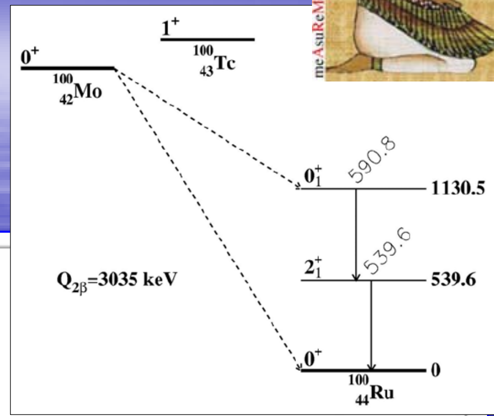
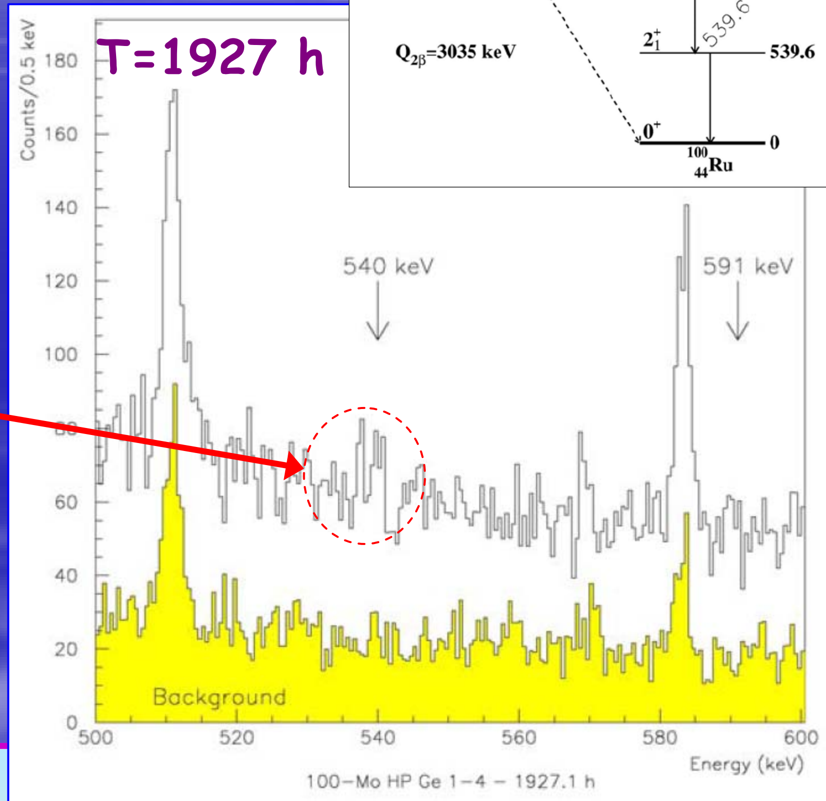
Search for 590.8 keV and 539.6 keV gamma quanta;

(detection efficiency ~2.5% -- Geant4)



Measured spectra (500-600 keV) with and without the Mo sample (T=1927 h)
Counting rate of the Mo sample is ~2.5 times higher than that of background in this region due to the Mo pollution



Considering this peak structure related with $2\beta2\nu$ decay of ^{100}Mo to 0^+_1 level of ^{100}Ru

$\Rightarrow T_{1/2} = 3\times10^{20}$ y

But no evidence of the second 591 keV peak

$\Rightarrow T_{1/2} > 6\times10^{20}$ y (90% C.L.)

Peaks at 511 keV and 583 keV related with ^{208}Tl decay and annihilation process (511 keV)

New data taking in progress after chemical purification of the ^{100}Mo source at LNGS

$\Rightarrow$ Expected sensitivity (1y) ~ 3×10^{21} y will allow to confirm or reject previous results

DATA TAKING IN PROGRESS

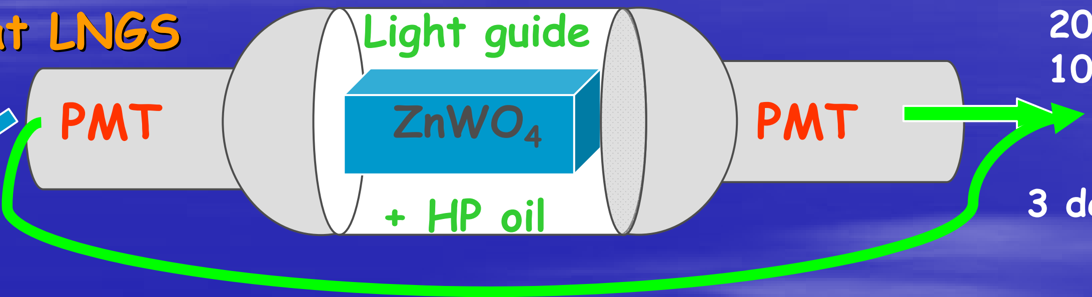
Search for $\beta\beta$ processes in ^{64}Zn

Preprint:
ROM2F/2007/13

- Low background $ZnWO_4$ scintillator, 20 x 19 x 40 mm -> 117 g mass
- Inside a cavity (filled up with high-pure silicon oil) ϕ 47 x 59 mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length.
- 2 Low background photomultiplier (PMT) EMI9265-B53/FL 3" diameter.

(All light guide wrapped by PTFE reflection tape)

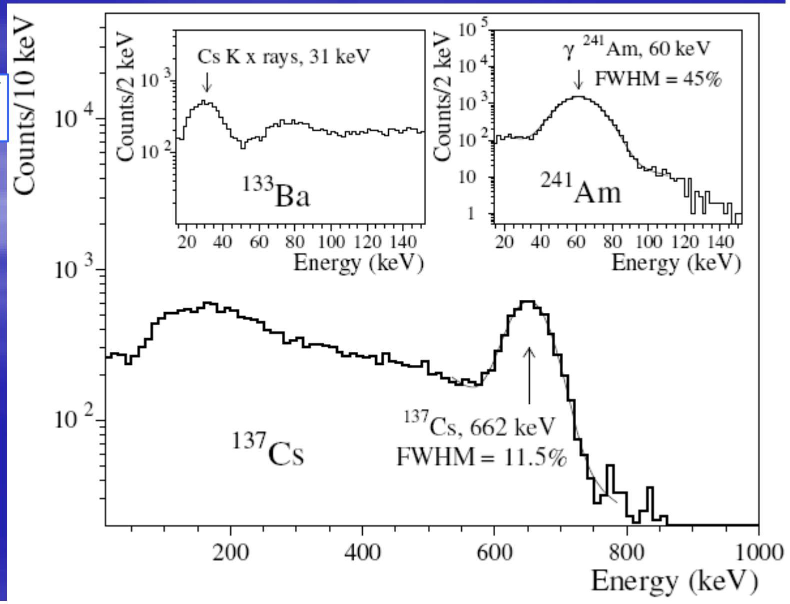
DAMA/R&D set-up at LNGS



20 MS/s TD over a 100 μs time window

pulses of $ZnWO_4$
3 decay components:
~0.7-7-25 μs

$$FWHM_\gamma(\text{keV}) = \sqrt{270(30) + 7.37(35) \cdot E_\gamma[\text{keV}]}$$



Low radioactive Cu box flushed with HP N_2

Passive shield
- 10 cm of high purity Cu
- 15 cm of low radioactive lead
- 1.5 mm of cadmium and
- 4 to 10 cm of polyethylene/paraffin

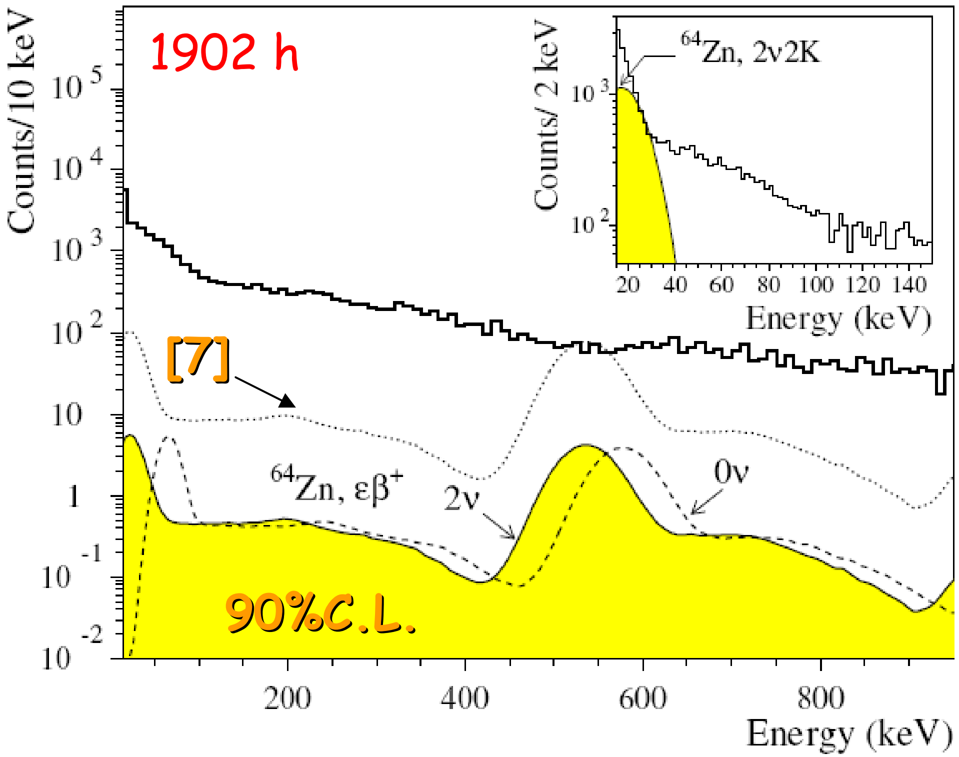
The whole shield closed inside a Plexiglas box also flushed with HP N_2

Search for $\beta\beta$ processes in ^{64}Zn

Preprint:
ROM2F/2007/13

Big natural abundance: 48.268%, M(^{64}Zn) – M(^{64}Ni) = 1095.7(0.7)keV

$\varepsilon\beta^+$ and 2ε energetically allowed



Decay channel	Experimental $T_{1/2}$, yr	
	Present work	Previous results
$0\nu\varepsilon\beta^+$	$> 2.2 \times 10^{20}$	$> 2.8 \times 10^{16}$ [8]
		$> 2.4 \times 10^{18}$ [9]
		$> 1.3 \times 10^{20}$ [10]
$2\nu\varepsilon\beta^+$	$> 2.1 \times 10^{20}$	$= (1.1 \pm 0.9) \times 10^{19}$ [7]
		$> 4.3 \times 10^{18}$ [9]
		$> 1.3 \times 10^{20}$ [10]
$0\nu 2K$	$> 4.0 \times 10^{18}$	$> 1.2 \times 10^{17}$ [18]
$2\nu 2K$	$> 6.2 \times 10^{18}$	$> 6.0 \times 10^{16}$ [8]
$0\nu 2\varepsilon$	$> 3.4 \times 10^{18}$	$> 7.0 \times 10^{17}$ [9]

[7] I. Bikit et al., Appl. Radiat. Isot. 46 (1995) 455.
[8] H. Kiel et al., Nucl. Phys. A 723 (2003) 499.
[9] F.A. Danevich et al., Nucl. Instr. Meth. A 544 (2005) 553.
[10] H.J. Kim et al., KEK Proc. 6 (2003) 205; report on the Int. Conf. on Current Problems in Nucl. Phys. At. Energy, Kiyv, Ukraine, May 29 { June 3, 2006.
[18] T. Bloxham et al., arXiv: 0707.2756v1 [nucl-ex].

Conclusions

Many rare processes have been investigated by DAMA coll. by developing and using various low background scintillators and set-ups increasing the sensitivities to various processes.

Here just results published in 2007 have been summarised.

1. New limits on α decay modes with a $Li_6Eu(BO_3)_3$ crystal

2. First measurement of α decay of ^{151}Eu with $CaF_2(Eu)$ detector

3. Preliminary results and improvement of the experiment to study $2\beta2\nu(0^+ \rightarrow 0^+_1)$ of ^{100}Mo with ~1 kg Mo sample

4. New limits on 2β processes in ^{64}Zn with $ZnWO_4$

Further works in progress and in preparation

Properties – $LaCl_3(Ce)$

Density [g/cm³]	3.79
Melting point [K]	1135
Thermal expansion coefficient [10^{-6}/°C]	11 along C-axis
Cleavage plane	[100]
Hygroscopic	yes
Wavelength of emission max. [nm]	350
Lower wavelength cutoff [nm]	313
Refractive index @ emission max	~1.9
Primary decay time [µs]	0.028
Light yield [photons/keVγ]	49
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	70-90

Properties – $CaF_2(Eu)$

Density [g/cm³]	3.18
Melting point [K]	1691
Thermal expansion coefficient [C^{-1}]	19.5×10^{-6}
Cleavage plane	<111>
Hardness (Mho)	4
Hygroscopic	no
Wavelength of emission max. [nm]	435
Lower wavelength cutoff [nm]	395
Refractive index @ emission max	1.47
Primary decay time [µs]	0.94
Light yield [photons/keVγ]	19
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	50

Mass-spectrometry of the CaF_2(Eu) crystal

Concentration of Eu determined with the ICP-MS (Inductively Coupled Plasma - Mass Spectrometry analysis).

Representative part of the CaF_2(Eu) crystal reduced to powder by mechanical treatment inside a cleaned polyethylene bag to avoid possible contamination.

Calcium fluoride rather insoluble in acids: several tests applying different solutions. The best solutions were as following: (a) H2SO4 95%; (b) mixture of 2 parts of HCl and 5 parts of HNO_3. Solubility of CaF_2 was about 75% and 65%, respectively.

The estimated effect of insoluble EuF_3 formation is negligible.

Six solutions were measured by ICP-MS analysis (3 of b, and 3 of a type): average value = $(0.4 \pm 0.1)\%$ (uncertainty takes into account the uncertainty on the sample preparation procedure).

The contamination by Nd, Sm, Gd, Hf, Os, Pt, Bi, Th, U (all these elements have α active isotopes) were also measured: <0.1 ppm were obtained for all of them.

Energy dependence of the α/β ratio

Because quenching of the scintillation light caused by α particles (in comparison with electrons) is due to the higher ionization density of α particles, such a behaviour of the α/β ratio can be explained by the energy dependence of the ionization density of α particles.

Increasing of α/β ratio at energies of α particles lower than 1.5 – 2 MeV was observed for $CdWO_4$ [1], and CaWO4 [2] scintillators. Similar behaviour of α/β ratio was measured very precisely for CsI(Tl) scintillator [3].

[1] F.A. Danevich et al., Phys. Rev. C 67 (2003) 014310.
[2] Yu.G. Zdesenko et al., Nucl. Instrum. Meth. A 538 (2005) 657.
[3] R. Gwin, R.B. Murray, Phys. Rev. 131 (1963) 501.

Fit was performed in the energy region with starting point from 215 to 230 keV (with step of 5 keV) and with final point from 340 to 410 keV.
In the most of the intervals the fit gives positive effect at the level of 1.2 –2.8 σ.

The best fit (χ^2/n.d.f. = 0.42), achieved in the interval 225 − 365 keV:
S = (302±232) counts.

Feldman-Cousins procedure ⇒ it is possible to conclude that observation of the effect is statistically significant and amplitude of the effect is inside the interval [5, 682] counts with 90% C.L. (or [98, 534] @ 68% C.L.).

$$T_{1/2} = 5.4^{+11.4}_{-2.4}(stat) \pm 1.4(syst) \times 10^{18} \text{ y}$$

The systematic error is related mainly with the uncertainty of the number of Eu nuclei in the crystal and with variation of the peak's area depending on the interval of the fit.

There are several α decaying nuclides with energy releases close to the ^{151}Eu value:

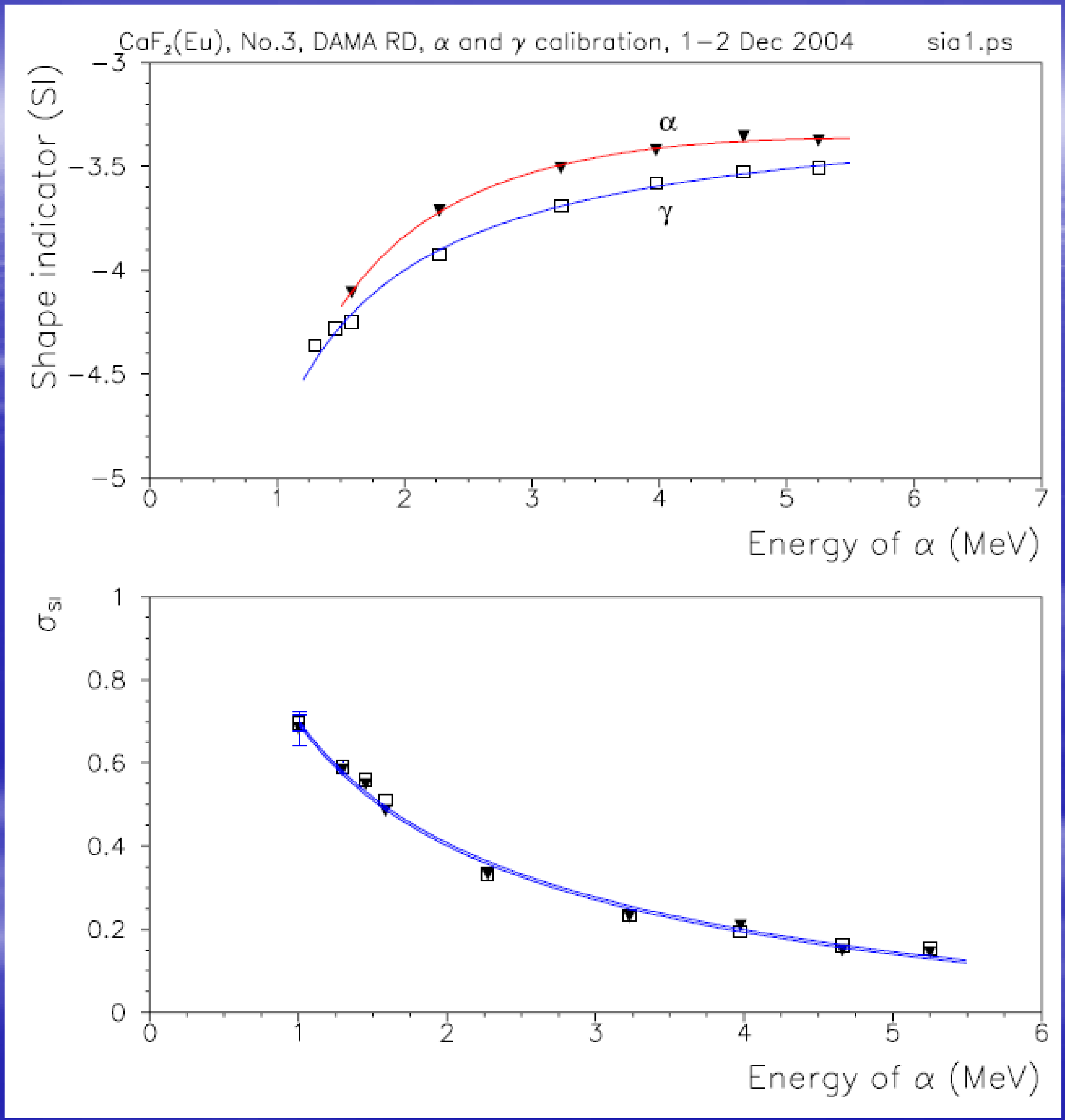
- ^{144}Nd (Q_α = 1.905 MeV),
- ^{148}Sm (Q_α = 1.986 MeV) and
- ^{152}Gd (Q_α = 2.203 MeV)

^{148}Sm has near the same abundance as ^{147}Sm; however, because of its big half-life (7×10^{15} y in comparison with 1.06×10^{11} y for ^{147}Sm), peak of ^{148}Sm should be near five orders of magnitude lower than peak of ^{147}Sm and, thus, cannot mimic alpha decay of ^{151}Eu.

Contaminations of the CaF_2(Eu) crystal by Nd and Gd are lower than 0.1 ppm that is known from the ICP-MS analysis.
With $T_{1/2} = 2.29 \times 10^{15}$ y and δ = 23.8%, ^{144}Nd could contribute not more than 10 events in the ^{151}Eu peak.

Contribution of ^{152}Gd ($T_{1/2} = 1.08 \times 10^{14}$ y and δ = 0.2%) should be even lower.

Thus, the observed alpha peak at ≈250 keV cannot be mimicked by some other α decaying nuclides present in the CaF_2(Eu) crystal.



CaF$_2$(Eu), No.3, DAMA RD, α and γ calibration, 1–2 Dec 2004
sia1.ps
Shape indicator (SI)
α
γ
Energy of α (MeV)
σ_{SI}
Energy of α (MeV)