On how to treat the X-ray spontaneous emission to get the lambda-value for collapse models

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"Is quantum theory exact ? The endeavor for the theory beyond standard quantum mechanics.

Second Edition FQT2015"

LNF, INFN, 23-25 September 2015

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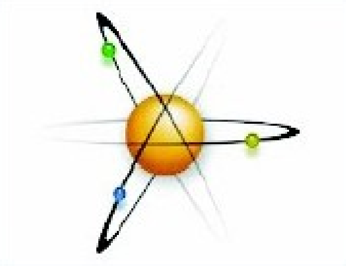
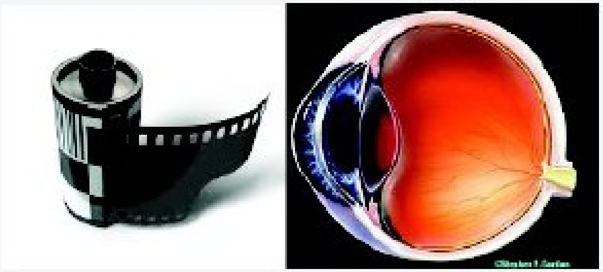
Which values for λ and r_c?



Microscopic world
(few particles)

$$\lambda \sim 10^{-8\pm2}\text{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)



Mesoscopic world
Latent image formation
+
perception in the eye
(~ 10^4 - 10^5 particles)

S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

$$\lambda \sim 10^{-17}\text{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world
(> 10^{13} particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

$$r_C = 1/\sqrt{\alpha} \sim 10^{-5}\text{cm}$$

Increasing size of the system

… upper limit on the reduction rate parameter from the spontaneous emission process …

… spontaneous photon emission

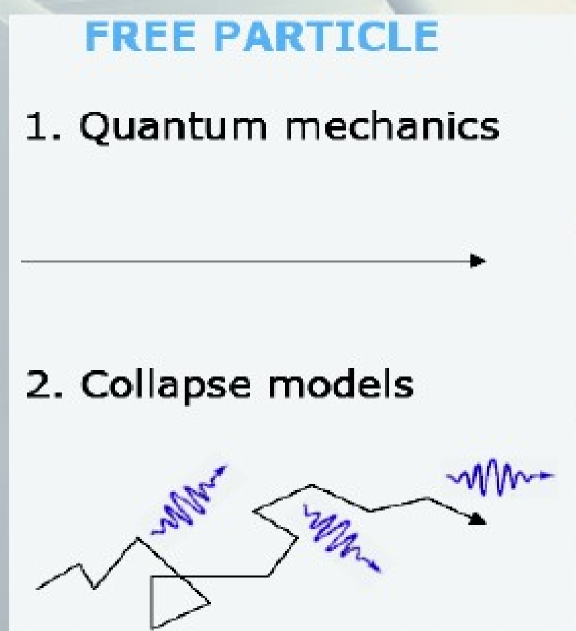
Besides collapsing the state vector to the position basis in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

↓

implies for a charged particle energy radiation (not present in standard QM) !!!

↓

The comparison between theoretical prediction and experimental results provide constraints on the parameters of the CSL model



$$\frac{d\Gamma_k}{dk} = \frac{e^2\lambda}{4\pi^2 r_c^2 m^2 k}$$

Q. Fu, Phys. Rev. A 56, 1806 (1997)

S.L. Adler, A. Bassi & S. Donadi, ArXiv 1011.3941

Expected X-ray rate from Ge low activity experiments

Q. Fu, Phys. Rev. A 56, 1806 (1997) → only upper limit on λ based on comparison with the radiation appearing in an isolated slab of Ge (raw data not background subtracted)

H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990)

Energy (keV)	Expt. upper bound (counts/keV/kg/day)	Theory (counts/keV/kg/day)
11	0.049	0.071
101	0.031	0.0073
201	0.030	0.0037
301	0.024	0.0028
401	0.017	0.0019
501	0.014	0.0015

TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

Comparison with the lower energy bin, due to the *non-relativistic constraint* of the CSL model

$$\left.\frac{d\Gamma_k}{dk}\right|_{th} = (2.74 \cdot 10^{-31}) \cdot 4 \cdot (8.29 \cdot 10^{24}) \cdot (8.6 \cdot 10^4) \cdot \frac{1}{k} < \left.\frac{d\Gamma_k}{dk}\right|_{ex}$$

$$\frac{e^2\lambda}{4\pi^2 r_c^2 m^2}$$

(Atoms / Kg) in Ge

4 valence electrons are considered

BE ~ 10 eV « energy of emitted γ ~ 11 keV

quasi-free electrons

1 day

Result → $\lambda < 0.55 \times 10^{-16}\ s^{-1}$ the GRW theory predicts 45% more radiation than the observed upper bound.

Result possibly biased by the punctual evaluation of the rate at one single energy bin.

Expected X-ray rate from Ge low activity experiments

Q. Fu, Phys. Rev. A 56, 1806 (1997) → only upper limit on λ based on comparison with the radiation appearing in an isolated slab of Ge (raw data not background subtracted)
H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990)

Result → $\lambda < 0.55 \times 10^{-16}\ s^{-1}$

According to S. L. Adler and F. M. Ramazanoglu, J. Phys. A40; 13395 (2007)
such value is to be divided by a factor 4π

↓

No mass-proportional $\lambda < 4.38 \times 10^{-18}\ s^{-1}$

for a mass proportional coupling …

$$\lambda \to \lambda \left(\frac{m_e}{m_N}\right)^2$$

mass-proportional $\lambda < 1.54 \times 10^{-11}\ s^{-1}$

Expected X-ray rate from Ge low activity experiments

S. L. Adler & F. M. Ramazanoglu (2007):

No mass-proportional $\lambda < 4.38 \times 10^{-18}\ s^{-1}$

mass-proportional $\lambda < 1.54 \times 10^{-11}\ s^{-1}$

More .. the preliminary TWIN data set resulted to under-estimate the rate for energies < 200 keV

(factor about 50 at 10 keV)

A new analysis (J. Mullin and P. Pearle, Phys. Rev. A 90, 052119 (2014)) employing improved data (B. Collett, P. Pearle, F. Avignone and S. Nussinov, Found. Phys.25, 1399 (1995)) gives:

No mass-proportional $\lambda < 2 \times 10^{-16}\ s^{-1}$

mass-proportional $\lambda < 8 \times 10^{-10}\ s^{-1}$

IGEX data analysis: using published data of the IGEX experiment

The IGEX experiment is a low-activity Ge based experiment dedicated to the $\beta\beta0\nu$ decay research. (C. E. Aalseth et al., IGEX collaboration Phys. Rev. C 59, 2108 (1999))

In (A. Morales et al., IGEX collaboration Phys. Lett. B 532, 8-14 (2002)) the published data acquired for an exposure of 80 *kg day* in the energy range:

$\Delta E = (4 - 49)\ keV \ll m_e = 512\ keV$ → compatible with the non-relativistic assumption.

Low-energy data from the IGEX RG-II detector (Mt = 80 kg day)

E (keV)	Counts	*E* (keV)	Counts	*E* (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	5
16.5	8	31.5	2	46.5	2
17.5	6	32.5	1	47.5	3
18.5	1	33.5	1	48.5	4

Analysis results and discussion

The performed fit enables to set an upper limit on the reduction rate parameter:

$$\left.\frac{d\Gamma_k}{dk}\right|_{th} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 k} = \frac{c\lambda}{k} < \frac{110}{k}$$

1) **assuming $r_c = 10^{-7}\ m$ → $\lambda < 1.4 \times 10^{-17}\ s^{-1}$**

1 O.M. improovement

3) **if a mass-proportional model is assumed (noise having a gravitational orgin?) then:**

$$\lambda \to \lambda\left(\frac{m}{m_N}\right)^2 \quad , \quad \left.\frac{d\Gamma_k}{dk}\right|_{th} = \frac{e^2\lambda}{4\pi^2 a^2 m_N^2 k}$$

→ $\lambda < 4.7 \times 10^{-11}\ s^{-1}$

Acta Phys. Polon. B46, (2015) 147

4) **taking the 22 outer electrons (down to the 3s orbit BE_{3s} = 180.1 eV) in the calculation:**

$\lambda < 2.5 \times 10^{-18}\ s^{-1}$	$\lambda < 8.5 \times 10^{-12}\ s^{-1}$
No mass-proportional	mass-proportional

2 O.M. improovement

J. Adv. Phys. 4, 263-266 (2015)

Upper limits on λ from different approaches

Limits from the spontaneous emission rate:

$\lambda < 2.5 \pm 0.2 \times 10^{-18}\ s^{-1}$	$\lambda < 8.5 \pm 0.5 \times 10^{-12}\ s^{-1}$
No mass-proportional	Mass-proportional

No mass-proportional EXCLUDED if white noise is assumed

Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	11-12 (2-3)	Dissociation of cosmic hydrogen	18 (9)
Decay of supercurrents (SQUIDs)	15 (6)	Heating of Intergalactic medium (IGM)	9 (0)
Spontaneous X-ray emission	**6 (-3)**	Heating of protons in the universe	13 (4)
Proton decay	19 (10)	Heating of Interstellar dust grains	116 (7)

Spontaneous emission including nuclear protons

When the emission of nuclear protons is also considered, the spontaneous emission rate is:

A. Bassi & S. Donadi

$$\frac{d\Gamma_k}{dk} = \left(N_P^2 + N_e\right) \frac{e^2\lambda}{4\pi^2 a^2 m_N^2 k}$$

provided that the emitted photon wavelength λ_{ph} satisfies the following conditions:

1) $\lambda_{ph} > 10^{-15}$ m (nuclear dimension) → protons contribute coherently

2) $\lambda_{ph} <$ (electronic orbit radius) → electrons and protons emit independently → NO cancellation

We consider in the calculation the 30 outermost electrons (down to 2s orbit) $r_e = 4 \times 10^{-10}$ m and take only the measured rate for $k > 35$ keV

Moreover $BE_{2s} = 1.4$ keV « k_{min} → electrons can be considered as *quasi-free*

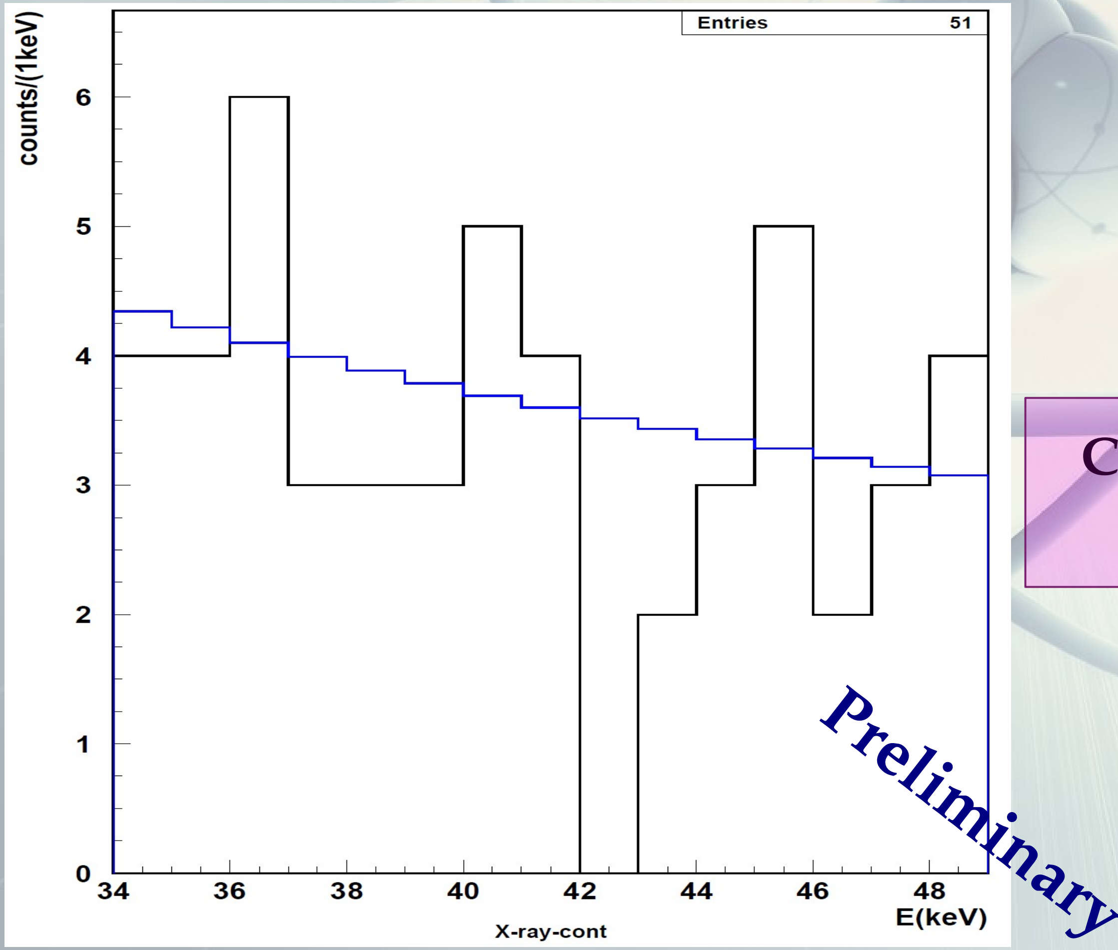
2) $\Delta E = (35 - 49)\ keV$ « $m_e = 512\ keV$ → compatible with the non-relativistic assumption.

Spontaneous emission including nuclear protons

The interval $\Delta E = (35 - 49)\ keV$ of the IGEX measured X-ray spectrum was fitted assuming the predicted energy dependence:

$$\frac{d\Gamma_k}{dk} = \frac{\alpha(\lambda)}{k}$$

Bayesian fit with $\alpha(\lambda)$ free parameter.



Fit result:

$\alpha(\lambda) = 148 \pm 21$

X^2/ n.d.f. = 0.8

Corresponding to the limit on the spontaneous emission rate:

$\lambda < 2.7 \times 10^{-13}\ s^{-1}$

Mass-proportional

3 O. M. improovement


A new approach

Probability distribution function of λ
theoretical information

Goal: obtain the probability distribution function PDF(λ) of the collapse rate parameter given:

- the theoretical information

Rate of spontaneously emitted photons as a consequence of *p* and *e* interaction with the stochastic field,

$$\frac{d\Gamma}{dE} = \left\{ \left(N_p^2 + N_e\right) \cdot \left(m\, n\, T\right) \right\} \frac{\lambda \hbar e^2}{4\pi^2 \epsilon_0 c^3 m_N^2 r_c^2 E}$$

(depending on λ)

as a function of *E*

(mass of the emitting material · number of atoms per unit mass · total acquisition time)

Probability distribution function of λ
theoretical information

Goal: obtain the probability distribution function PDF(λ) of the collapse rate parameter given:

- the theoretical information

$$\frac{d\Gamma}{dE} = \left\{ \left(N_p^2 + N_e\right) \cdot \left(m\, n\, T\right) \right\} \frac{\lambda \hbar e^2}{4\pi^2 \epsilon_0 c^3 m_N^2 r_c^2 E}$$

Provided that the wavelength of the emitted photon:

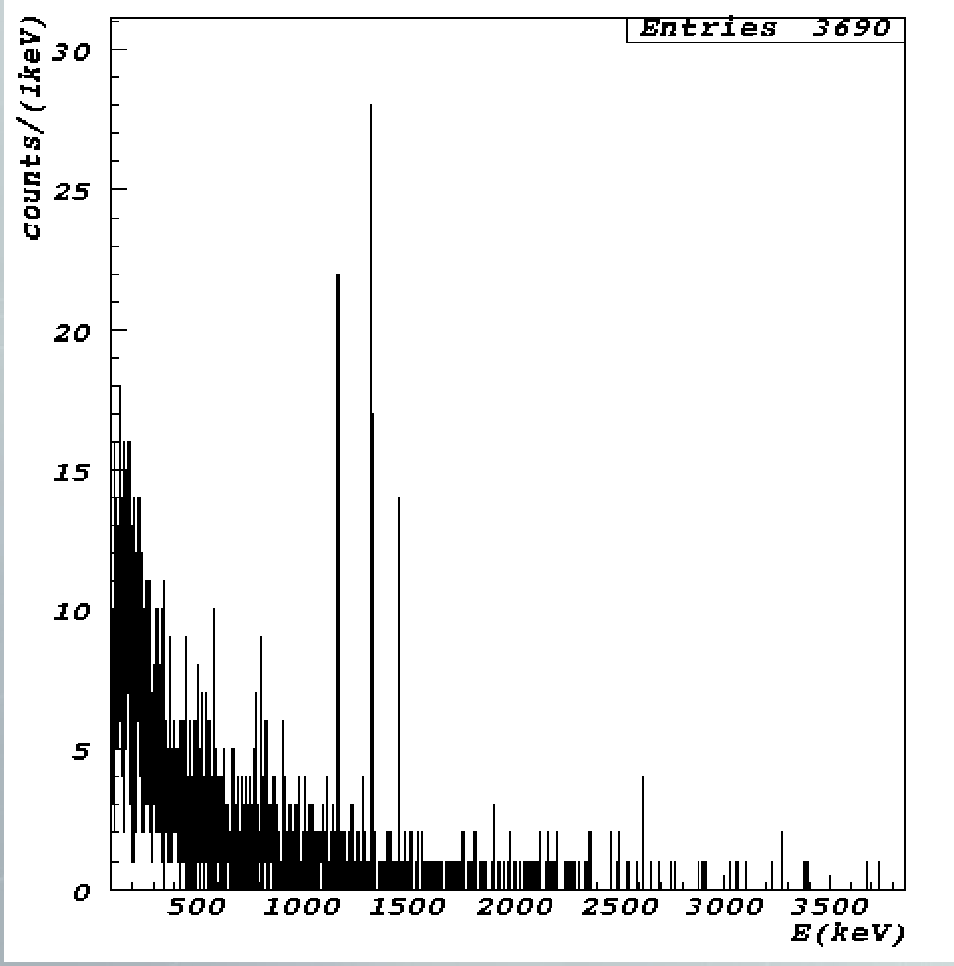
- is greater then the nuclear dimensions → protons contribute coherently
- is smaller then the lower electronic orbit → protons and electrons emit independently
- guarantees that electrons and protons can be considered as non-relativistic.

Probability distribution function of λ

experimental information

Goal: obtain the probability distribution function PDF(λ) of the collapse rate parameter given:

- the experimental information



X-ray measurements performed in the very low background environment of the LNGS (INFN) with low activity Germanium based detectors.
(three months data taking with 2kg germanium active mass)

According with theory constrains we use the range:

$$\Delta E = (100 \div 3800) keV$$

Probability distribution function of λ
experimental information

Goal: obtain the probability distribution function PDF(λ) of the collapse rate parameter given:

- the experimental information

total number of counts in the selected energy range:

$$f(z_c) = \frac{\Lambda_c^{z_c} e^{-\Lambda_c}}{z_c!}$$

besides the background from standard processes let's turn on the spontaneous emission contribution ...

- z_b = number of counts due to background,
- z_s = number of counts due to signal,
- $z_c = z_b + z_s$; $z_s \sim P_{\Lambda_s}$; $z_b \sim P_{\Lambda_b}$,

$$f(z_c|P_{\lambda s}, P_{\lambda b}) = \sum_{z_s, z_b} \delta_{z_c, z_s+z_b} \, f(z_s|P_{\lambda s}) \, f(z_b|P_{\lambda b}) = \frac{(\Lambda_s + \Lambda_b)^{z_s+z_b} \, e^{(\Lambda_s+\Lambda_b)}}{z_c!}$$

Probability distribution function for λ

According with the Bayes theorem: $f(\lambda|\mathrm{ex},\mathrm{th}) = f(\mathrm{ex}|\lambda)\cdot f(\lambda|\mathrm{th})$

let us assume a conservative prior [S. L. Adler, JPA 40, 2935 (2007)]

$$f(\lambda|\mathrm{th}) = 1 \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$
$$f(\lambda|\mathrm{th}) = 0 \qquad \lambda > 10^{-6}\mathrm{s}^{-1}$$

PDF(λ) is:

$$f(\lambda|\mathrm{ex},\mathrm{th}) = \frac{(\Lambda_s(\lambda)+\Lambda_b)^{z_c}\cdot e^{-(\Lambda_s(\lambda)+\Lambda_b)}}{z_c!} \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$
$$f(\lambda|\mathrm{ex},\mathrm{th}) = 0 \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$

Advantages .. - possibility to extract unambiguous limits corresponding to the probability level you prefer,

- *f*(λ) can be updated with all the experimental information at your disposal by updating the likelihood,

- competing or future models can be simply implemented

Probability distribution function for λ

PDF(λ) is:

$$f(\lambda|\mathrm{ex,th}) = \frac{(\Lambda_s(\lambda)+\Lambda_b)^{z_c}\cdot e^{-(\Lambda_s(\lambda)+\Lambda_b)}}{z_c!} \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$

$$f(\lambda|\mathrm{ex,th}) = 0 \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$

Advantages .. - possibility to extract unambiguous limits corresponding to the probability level you prefer,

- *f*(λ) can be updated with all the experimental information at your disposal by updating the likelihood,

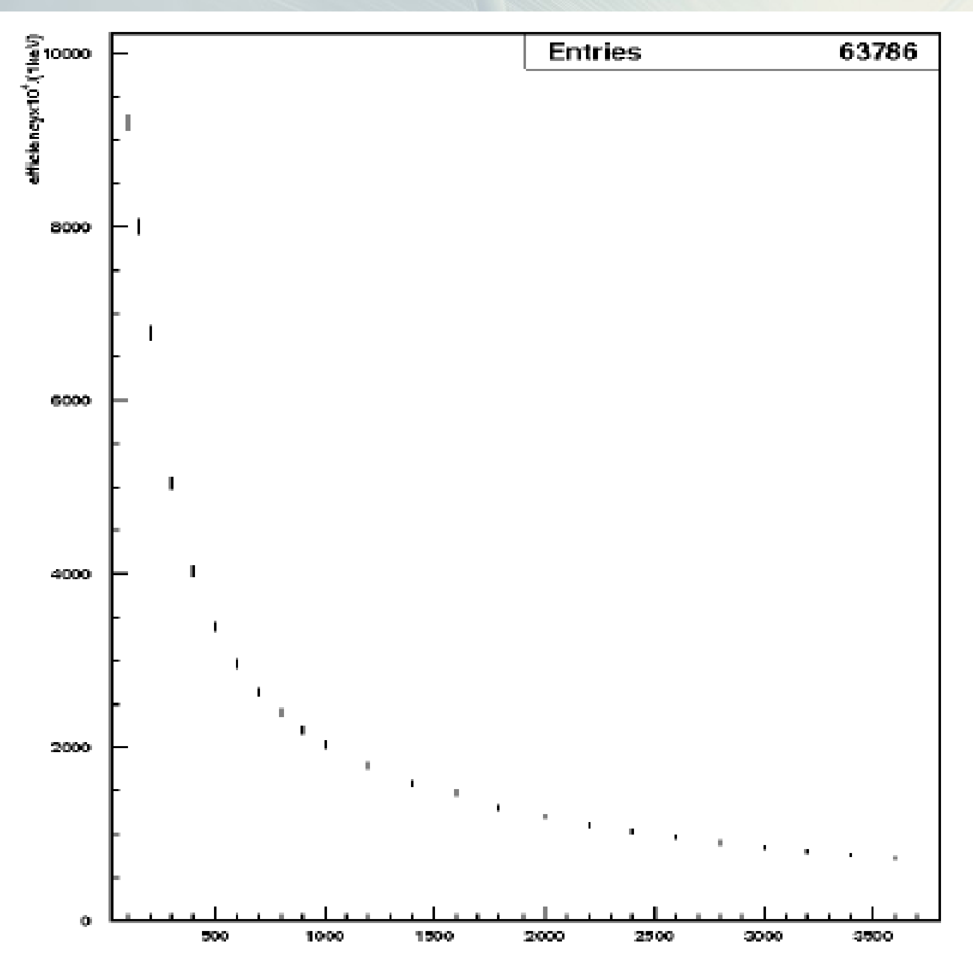
- competing or future models can be simply implemented (ex. coloured noises)

In practice .. $\Lambda_s(\lambda)$

Each material of the detector contributes to the signal rate with different:

***m*, *n* and $\boldsymbol{\varepsilon}(E)$**

$\boldsymbol{\varepsilon}(E)$ depends on the material and the geometry of the detector.



Simulated detection eciency for γs produced inside the Germanium detector, multiplied by 10^4

Photon detection efficiencies obtained by means of MC simulations, ganerating γs in the range (E1 – E2) (25 points for each material).

In practice .. $\Lambda_s(\lambda)$

Each material of the detector contributes to the signal rate with different:

m, n **and ε(*E*)**

ε(*E*) **depends on the material and the geometry of the detector.**

efficiency distributions fitted to obtain the efficiency functions:

$$\epsilon_i(E) = \sum_{j=0}^{ci} \xi_{ij} E^j$$

to obtain the signal predicted by theory & processed by the detector

$$z_s(\lambda) = \sum_i \int_{E_1}^{E_2} \frac{d\Gamma}{dE}\bigg|_i \epsilon_i(E)\, dE = $$
$$= \sum_i \int_{E_1}^{E_2} N_{pi}^2\, \alpha_i\, \beta\, \frac{\lambda}{E} \sum_{j=0}^{ci} \xi_{ij} E^j\, dE$$
$$= 1.328824 \cdot 10^{15} \lambda.$$

with:

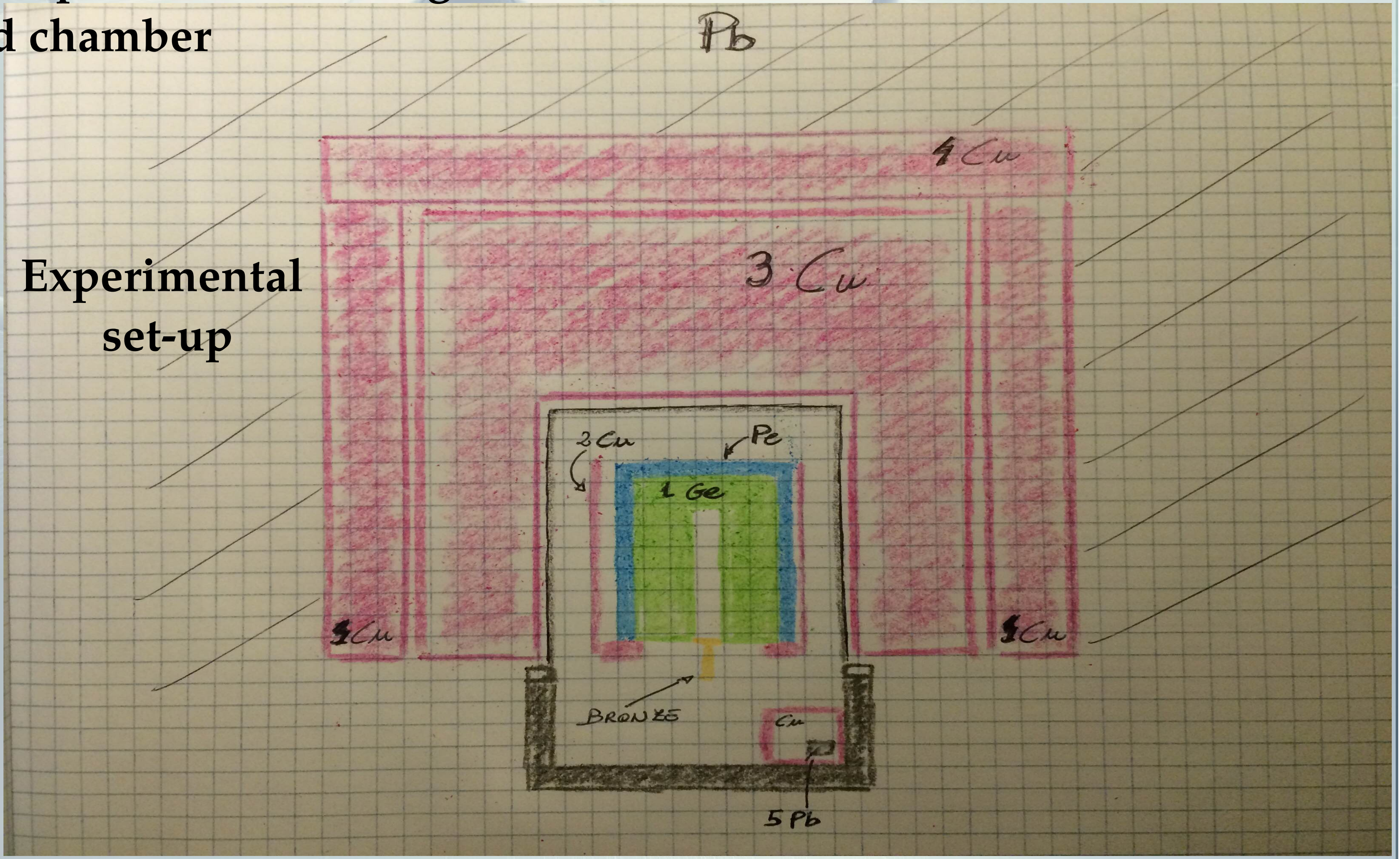
$$\alpha_i = m_i n_i T,$$
$$\beta = \frac{\hbar e^2}{4\pi^2 \epsilon_0 c^3 m_N^2 r_c^2}$$

In practice .. $\Lambda_s(\lambda)$

The predicted numbers of signal counts, with (left) and without (right), efficiency correction, for the more massive components of the detector:

1 = Ge crystal
2 = inner Copper
3 = Copper block + plate (surrounding the detector)
4 = Copper shield chamber
5 = Lead shield.

Experimental set-up



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component	$z_i(\lambda)/(10^{-15}\cdot\lambda)$	$z_i(\lambda)/(10^{-15}\cdot\lambda)$ w. o. correction
1	1.237957	3.292720
2	$7.331631\cdot10^{-2}$	$9.925296\cdot10^{-1}$
3	$1.198010\cdot10^{-2}$	$2.057934\cdot10^{+1}$
4	$3.194445\cdot10^{-3}$	$8.416646\cdot10^{+1}$
5	$2.376519\cdot10^{-3}$	3.174667

The expected number of counts for signal events: $\Lambda_s(\lambda) = 1.328824\cdot10^{15}\lambda + 1.$

In practice .. Λ_b

Evaluation of the background:
simulation of the radionuclides decay for which materials of the setup contribute taking into account for the emission probabilities and the decay scheme of each radionuclide. For the moment the following contributions were considered:

- **Co60 from the inner Copper (14 counts)**
- **Co60 from the Copper block + plate (562 counts)**
- **Co58 from the Copper block + plate (117 counts)**
- **K40 from Bronze (5 counts)**
- **Ra226 from Bronze (0 counts)**
- **Bi214 from Bronze (2 counts)**
- **Pb214 from Bronze (1 counts)**
- **Bi212 from Bronze (1 counts)**
- **Pb212 from Bronze (0 counts)**
- **Tl208 from Bronze (1 counts)**
- **Ra226 from Poliethylene (0 counts)**
- **Bi214 from Poliethylene (0 counts)**
- **Pb214 from Poliethylene (0 counts).**

In practice .. Λ_b

Evaluation of the background:
simulation of the radionuclides decay for which materials of the setup contribute taking into account for the emission probabilities and the decay scheme of each radionuclide. For the moment the following contributions were considered:

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- Bi214 from Bronze (2 counts)
- Pb214 from Bronze (1 counts)
- Bi212 from Bronze (1 counts)
- Pb212 from Bronze (0 counts)
- Tl208 from Bronze (1 counts)
- Ra226 from Poliethylene (0 counts)
- Bi214 from Poliethylene (0 counts)
- Pb214 from Poliethylene (0 counts).

measured activities

$$\text{counts} = \frac{m_i\, A_{ij}\, T\, z_{b,ij}}{10^8}$$

detected MC γs

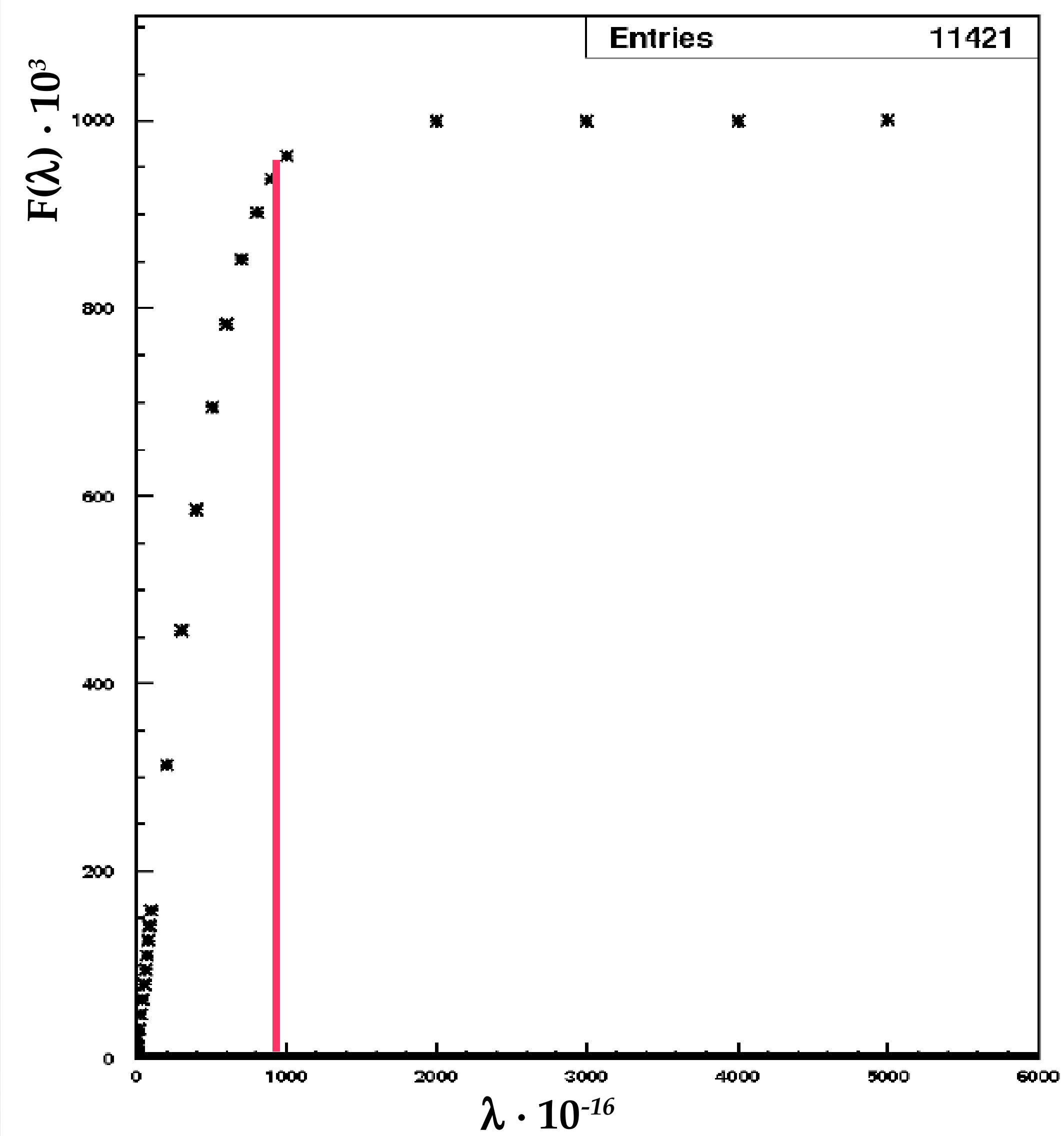
simulated events

We are still far from a satisfactory description of background :-(ongoing work

In a bright optimistic future ..

99% <u>of the experimental spectrum is explained in terms of standard processes</u>

put z_c , $\Lambda_s(\lambda)= a\lambda + 1$, Λ_b in the cumulative distribution function:



$$F(\lambda) = 1 - \frac{\Gamma(z_c + 1, a\lambda + 1 + \Lambda_b)}{\Gamma(z_c + 1, 1 + \Lambda_b)}$$

extract the limit at the desired probability level ...

ex.

$\lambda < 9 \cdot 10^{-14}$ with a probability of 95%


Thanks