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Experimental constrains on the Continuous Spontaneous Localization model from spontaneous radiation emission

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The work presented in this paper aimed to obtain new, more stringent, limits on the parameters of the Continuous Spontaneous Localization collapse model. The result is accomplished by performing a Bayesian analysis of the X-ray emission data collected by the IGEX collaboration, compared with the spontaneous photon emission which is predicted by collapse models. The most stringent limits on the collapse rate λ and the correlation length r_C of the CSL model are obtained , with respect to any other method, over a broad range of the parameters space.

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1. Collapse models and CSL

Collapse models aim to solve the measurement problem of quantum mechanics and explain the quantum-to-classical behaviour transition without postulating the wave packet reduction [1]. According to these phenomenological models a non-linear term and a stochastic term are to be introduced in the Schrödinger equation, the latter describing the quantum state interaction with a stochastic noise field. The two terms determine the system wave function collapse in the position basis, moreover the strength of the collapse increases with the mass of the object (amplification mechanism). Collapse models then explain why quantum superpositions of macroscopic objects are not observed, but contemporary, since the effect of the non-linear interaction with the noise field is very small, the dynamics of microscopic objects is dominated by the standard Schrödinger evolution.

We will focus, in particular, on the Continuous Spontaneous Localization (CSL) model [2, 3, 4], which is one of the most relevant and well-studied collapse models in the literature. Two phenomenological parameters (λ and r_C) are introduced in the model. The parameter λ has the dimensions of a rate and sets the strength of the collapse, while r_C is a correlation length which determines the spatial resolution of the collapse: for superposition with size much smaller than r_C, the collapse is much weaker compared to the case when the superposition has a delocalization much larger than r_C. The originally proposed values for λ and r_C are [2] $\lambda = 10^{-16}$ s^{-1}, $r_C = 10^{-7}$ m. Higher values for λ were however put forward [5], up to $\lambda = 10^{-8\pm2}$ s^{-1}.

As a consequence of the interaction with the stochastic field, particles are subject to a diffusion process which causes, for charged particles, an extra emission of electromagnetic radiation, not predicted by the standard quantum mechanics (see Ref. [6]). The measurement of this radiation (usually referred as *spontaneous radiation*) allows to set limits on λ and r_C (see also Ref. [7]) which strongly reduces the allowed region of the parameters space.

2. The collapse rate parameter λ

The energy distribution of the spontaneous radiation rate (Γ) emitted by free electrons (as a function of λ and r_C) was first predicted by Fu [6] and later on studied in more detail in [8, 9, 10], in the framework of the non-relativistic CSL model. If the collapsing stochastic field is assumed to be coupled to the particle mass density (mass proportional CSL model), it assumes the following expression:

$$\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 r_C^2 m_N^2 E}, \tag{2.1}$$

where e is the charge of the proton, m_N represents the nucleon mass and E is the energy of the emitted photon. In the non-mass proportional case m_N is to be changed for m_e in Eq. 2.1. Fu exploited the measured radiation emitted by an isolated slab of Germanium, measured in Ref. [11] at an energy of 11 keV, to extract the following upper limits on λ, based on the expected spectrum in Eq. 2.1.

$$\lambda \leq 2.20 \cdot 10^{-10} s^{-1} \quad \text{mass prop.}, \tag{2.2}$$

$$\lambda \leq 0.55 \cdot 10^{-16} s^{-1} \quad \text{non-mass prop.,} \tag{2.3}$$

assuming that the correlation length value is $r_C = 10^{-7}$ m. In his estimate, Fu considered the contribution to the spontaneous X-ray emission of the four valence electrons in the Germanium atoms. Such electrons can be considered as *quasi-free*, since their binding energy (of the order of $\sim$10 eV) is much less than the emitted photons' energy. In Ref. [5], the author argues that an erroneous value for the fine structure constant is used in Ref. [6]. This correction is taken into account in the analysis described in Section 4. Further, the preliminary TWIN data set [11] used by Fu to estimate the upper limit on λ turned out to be underestimated by a factor of about 50 at 10 keV.

A new analysis was performed in Ref. [12]. Based on the improved data presented in Ref. [13], the limits corresponding to the footnote [7] in Ref. [12], for the cases of mass proportional and non-mass proportional CSL models, were:

$$\lambda \leq 8 \cdot 10^{-10} s^{-1} \quad \text{mass prop.,} \tag{2.4}$$

$$\lambda \leq 2 \cdot 10^{-16} s^{-1} \quad \text{non-mass prop..} \tag{2.5}$$

3. A new upper limit on λ

The analysis presented in this work aims to set a more stringent limit on the collapse rate parameter λ by using the X-ray emission spectrum measured by the IGEX experiment [14]. IGEX is based on low-activity Germanium detectors, the experiment was originally conceived to investigate the neutrinoless double beta decay ($\beta\beta 0\nu$). The published data set which is used in this work (see Ref. [15]) corresponds to 80 kg day exposure, it was collected to search for a dark matter WIMPs signal.

For the measurement in Ref. [15], one of the IGEX detectors of 2.2 kg (active mass of about 2 kg) was used. The detector, the cryostat and the shielding were fabricated following ultra-low background techniques, in order to minimize the radionuclides emission, which represents the main background source in the measured X-ray spectrum (shown in Figure 1 as a black distribution). Moreover, a cosmic muon veto covered the top and the sides of the shield. The experiment had an overburden of 2450 m.w.e., reducing the muon flux to the value of $2 \cdot 10^{-7}$ cm^{-2} s^{-1}. The two main sources of inefficiency are represented by the muon veto anti-coincidence and the pulse shape analysis. The probability of rejecting non-coincident events with the muon veto was found to be less than 0.01. The loss of efficiency introduced by the pulse shape analysis resulted to be negligible for events above 4 keV.

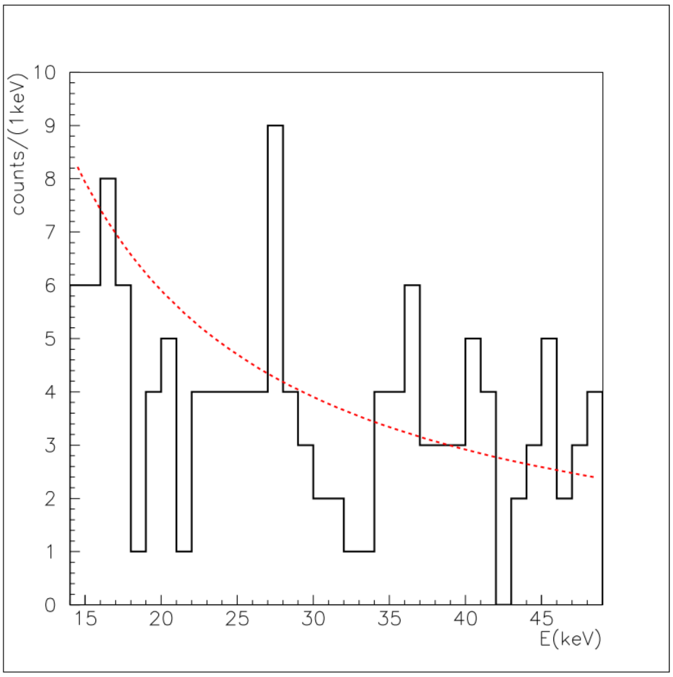

Figure 1: Fit of the X-ray emission spectrum measured by the IGEX experiment [14, 15], using the theoretical fit function Equation (4.1). The black line corresponds to the experimental distribution; the red dashed line represents the fit. See the text for more details.

The X-ray spectrum (Figure 1) ranges in the interval $(4.5 \div 48.5)$ keV, which is compatible with the non-relativistic assumption for electrons, used to derive Eq. (2.1).

4. Data analysis

The X-ray experimental spectrum published in [15] is compared with the predicted rate in Eq. 2.1, by taking into account the spontaneous emission of the 30 outermost electrons of the Ge atoms considered as *quasi-free*. We restricted our analysis to the energy range $\Delta E = (14.5 \div 48.5)$ keV of the experimental spectrum [15], for which the binding energy of the lower lying electronic orbit (the 2s orbit) is still one order of magnitude lower than 14.5 keV, justifying the *quasi-free* hypothesis.

The X-ray spectrum is fitted in the interval ΔE by minimising a χ^2 function. The expected number of counts for each bin of 1 keV is assumed to be described by Eq. 2.1:

$$\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}. \tag{4.1}$$

The χ^2 minimisation presumes that the bin contents y_i (number of counts in the energy bin E_i) follow Gaussian distributions. Strictly speaking, the y_is are Poissonian stochastic variables; nevertheless, the approximation is reasonable for $y_i \geq 5$; this constraint is then used for the fit. The result of the fit is shown in Figure 1 (red dashed line). For the free parameter of the fit, the minimization gives the value $\alpha(\lambda) = 115 \pm 17$, corresponding to a reduced $\chi^2/(n.d.f. - n.p.) = 0.9$. $n.d.f.$ represents the number of degrees of freedom, $n.p.$ is the number of free parameters of the fit. $\alpha(\lambda)$ is also considered to follow a Gaussian distribution with a good approximation. An upper limit can then be set as $\alpha(\lambda) \leq 143$ with a probability of 95%. Correspondingly, an upper limit on the parameter λ can be extracted using Eq. (2.1):

$$\frac{d\Gamma(E)}{dE} = c\,\frac{e^2\lambda}{4\pi^2 r_C^2 m^2 E} \leq \frac{143}{E}, \tag{4.2}$$

where the factor c is given by:

$$c = \left(8.29 \times 10^{24}\,\frac{\text{atoms}}{\text{kg}}\right) \cdot (80\,\text{kg day}) \cdot \left(8.64 \times 10^{4}\,\frac{\text{n. of seconds}}{\text{day}}\right) \cdot (30), \tag{4.3}$$

the first bracket accounts for the particle density of Germanium, the second represents the amount of emitting material expressed in kg day, the third term is the number of seconds in one day and 30 represents the number of spontaneously emitting electrons for each Germanium atom. Applying Equation (4.2), the following upper limits for the reduction rate parameter are obtained, with a probability of 95%:

$$\lambda \leq 8.1 \cdot 10^{-12} s^{-1} \quad \text{mass prop.}, \tag{4.4}$$

$$\lambda \leq 2.4 \cdot 10^{-18} s^{-1} \quad \text{non-mass prop..} \tag{4.5}$$

In order to obtain the limits in Equations (4.4) and (4.5), two implicit assumptions are made on the experimental input [15]. First, the measured spectrum is assumed to be background free, that is to say that the upper limit on λ corresponds to the case in which all the measured X-ray emission would be produced by spontaneous emission processes. This ansatz is conservative, and is imposed by our ignorance regarding the contribution from known emission processes to the measured rate. The second assumption, which is consistent with the analysis presented in Ref. [15], is that the detector efficiency, in the range ΔE, is one, and that the un-efficiencies which are introduced by the muon veto anticoincidence and the pulse shape analysis, performed to extract the experimental spectrum in Ref. [15], are very small for events above 4 keV.

Having in mind these assumptions, the measured X-ray counts in the range ΔE can be re-analysed in terms of their low-events Poissonian statistics. The number of counts y_is in each energy bin E_i can be considered as independent stochastic variables following the distributions:

$$G(y_i|P,\Lambda_i) = \frac{\Lambda_i^{y_i} e^{-\Lambda_i}}{y_i!}, \tag{4.6}$$

where P denotes the Poisson distribution function. The expected numbers of counts per bin Λ_i are indicated with capital letters, not to be confused with the spontaneous collapse rate λ. Let us define:

$$y = \sum_{i=1}^{n} y_i \quad , \quad \Lambda = \sum_{i=1}^{n} \Lambda_i \tag{4.7}$$

where n is the total number of 1 keV bins in the range ΔE, y and Λ are the total number of counts and the expected number of total counts, respectively. Here, y is distributed according to a Poissonian of parameter $\Lambda(\lambda)$, where the dependence on the collapse rate parameter, which follows the theoretical input, was explicitly indicated.

According to the Bayes theorem, the probability distribution function of $\Lambda(\lambda)$, given the measured y, assuming a uniform prior, is given by:

$$G'(\Lambda|G(y|P,\Lambda)) \propto \Lambda(\lambda)^y e^{-\Lambda(\lambda)}, \tag{4.8}$$

which means that $G'(\lambda)$ is proportional to a gamma probability distribution. Due to the assumption that the background is negligible, $\Lambda(\lambda)$ also represents the expected number of total signal counts y_s, where y_s is a Poissonian variable. Thus, according to Equation (4.2):

$$\Lambda(\lambda) = y_s + 1 = \sum_{i=1}^{n} c \frac{e^2\lambda}{4\pi^2 r_C^2 m^2 E_i} + 1 = \sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i} + 1. \tag{4.9}$$

Substituting Equation (4.9) for Equation (4.8), the probability distribution function for the collapse rate parameter can then be obtained:

$$G'(\lambda|G(y|P,\Lambda)) \propto \left(\sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i} + 1\right)^y e^{-\left(\sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i}+1\right)}, \tag{4.10}$$

where the measured total number of counts is $y = 130$. Calculating the cumulative distribution function

$$\int_0^{\lambda_0} G'(\lambda|G(y|P,\Lambda))\, \mathrm{d}\lambda, \tag{4.11}$$

the following upper limits can be obtained on the collapse rate parameter, setting r_C to the value 10^{-7} m, corresponding to a probability level of 95%

$$\lambda \leq 6.8 \cdot 10^{-12}\, s^{-1} \quad \text{mass prop.}, \tag{4.12}$$

$$\lambda \leq 2.0 \cdot 10^{-18}\, s^{-1} \quad \text{non-mass prop..} \tag{4.13}$$

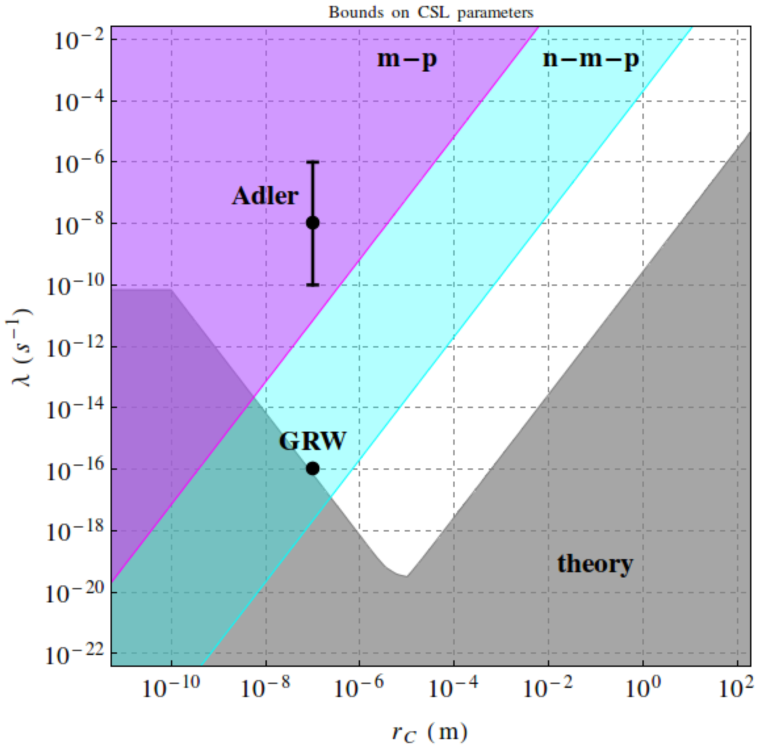

Figure 2: Mapping of the $\lambda - r_C$ Continuous Spontaneous Localization (CSL) parameters: the originally proposed theoretical values (GRW, Adler) are shown as black points; the region excluded by theory (theory) is represented in gray. The excluded region according to our analysis is shown in cyan for the non-mass proportional case (n-m-p) and in magenta for the mass proportional case (m-p).

5. Map of the CSL parameters plane

In Figure 2, we present the mapping of the $\lambda - r_C$ parameters of the CSL model, where the originally proposed theoretical values are shown, together with our results. The region excluded by theoretical arguments is represented in gray. This theoretical bound (see Ref. [16]) is obtained by requiring that a single-layered graphene disk of radius ∼0.01 mm is localized within ∼10 ms (these are the minimum resolution and perception time of the human eye, respectively).

The region excluded by this analysis is shown in cyan for the non-mass proportional case and in magenta for the mass proportional case. Figure 2 can be compared with Figure 2 in Ref. [17], where the mapping is obtained using other measurements. It is interesting to note that, for a collapse induced by a white noise, the allowed parameter space is confined to a drastically reduced region.

6. Conclusions and perspectives

In this work the X-ray spectrum measured by the IGEX Germanium detector was analysed, with the aim to estimate the possible contribution of the spontaneous radiation emission. Spontaneous radiation is a consequence of the interaction of the charged particles with the stochastic noise field, which causes the wave function reduction according to collapse models. The Bayesian analysis of the spectrum allowed to obtain an exclusion map of the CSL collapse model parameters. The results shown in Figure 2 can be summarized as follows:

- the non-mass proportional model for a white noise scenario can be excluded by our analysis,
- the higher value on λ [5] can be excluded for a white noise scenario, in both mass proportional and non-mass proportional models,
- the measurement of the spontaneous radiation allows to obtain of the most stringent limits on the CSL collapse model parameters, with respect to any other method, in a broad range of the parameter space (see also Ref. [17] for comparison).

We are presently exploring the possibility of performing a new measurement that will allow an improvement of at least one order of magnitude on the collapse rate parameter λ, thus allowing to reject a larger region of the parameters plane.

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