Collapse models under test by high sensitivity γ-ray and X-ray measurements

Catalina Curceanu[1,2], Kristian Piscicchia[3,1], Massimiliano Bazzi[1], Mario Bragadireanu[2,1], Michael Cargnelli[4,1], Alberto Clozza[1], Luca De Paolis[1], Raffaele Del Grande[5,1], Carlo Guaraldo[1], Mihail Iliescu[1], Matthias Laubenstein[6], Johann Marton[4,1], Marco Miliucci[1], Fabrizio Napolitano[1], Alessio Porcelli[4,1], Alessandro Scordo[1], Francesco Sgarmella[1], Hexi Shi[4], Diana Laura Sirghi[1,2], Florin Sirghi[1,2], Oton Vazquez Doce[1] and Johann Zmeskal[4,1]

[1] *Laboratori Nazionali di Frascati, INFN, Italy*
[2] *IFIN-HH, Institutul National pentru Fizica si Inginerie Nucleara Horia Hulubei, Romania*
[3] *Centro Ricerche Enrico Fermi – Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Italy*
[4] *Stefan-Meyer-Institute for subatomic physics, Austrian Academy of Science, Austria*
[5] *Excellence Cluster Universe, Technische Universität München, Germany*
[6] *Laboratori Nazionali del Gran Sasso, INFN, Italy*

The article reviews our recent experimental results on the Continuous Spontaneous Localization (CSL) model and on the gravity related collapse model developed by Diósi and Penrose (DP). These models of dynamical reduction of the wave function consist in non-linear and stochastic modifications of the Schröedinger equation, which lead to a progressive breakdown of the superposition principle, as the size of the system increases. We performed a high sensitivity survey of the spontaneous radiation phenomenon, predicted by the collapse models, in a dedicated experiment operated in the extremely low background of the Gran Sasso underground National Laboratory of INFN in Italy. Our studies set the strongest bounds on the CSL parameters, in a broad region of the parameters space, and rule out the DP in its present formulation.

Keywords: Collapse Models; Spontaneous Radiation; Germanium Detectors.

1. Dynamical collapse models and spontaneous radiation

Quantum Theory (QT) is the basis of our understanding of the physical world. Since its inception QT successfully described plenty of puzzling experimental phenomena, it explained the spectrum of the black body radiation and the atomic structure, it was the cornerstone of the development of modern chemistry, of nuclear physics and of quantum field theory, just to give some examples, and presently fuels the growth of vanguard technologies. Despite its success and the outstanding precision of the experimental validations, QT still contains a conundrum in its grounding pillars. Why the superposition principle, characterizing the evolution of microscopic systems, does not carry over to macroscopic objects? Why in the act of measuring the deterministic dynamics is replaced by a probabilistic behaviour governed by the Born rule?

Models of dynamical reduction of the wave function represent phenomenological, and testable, concrete solutions to the problem (see e.g.,[1–8] for a review and references see also[9]). They consist in non-linear and stochastic modifications of the

Schröedinger equation, which preserve the QT predictions in the microscopic regime, and go over to classical mechanics in the macroscopic limit, by breaking down the quantum linear evolution proportionally to the growing size of the system.

Besides interferometric experiments (see e.g.[10–14]), which aim to measure the interference pattern of the spatial superposition which is created in an interferometer, collapse models can be also probed with indirect tests (see e.g.[15–27]). Common denominator of this second class of experiments is to exploit the random motion associated to the collapse mechanism, which allows to test the effect of the models predictions on macroscopic objects. Clear advantage is the magnification effect, which leads to the stronger constraints on the collapse models, this is the case of micrometer cantilever,[16] gravitational wave detectors[28,29] and X/γ-ray measurements,[25–27] the latter being the subject of this paper.

We will review in this paper our latest experimental results on the Continuous Spontaneous Localization (CSL) and on the Diósi-Penrose (DP) models. In the CSL model[4–6] the non-linear and stochastic terms are characterized by the interaction with a continuous set of independent noises, with zero average, Gaussian correlation in space and, in the simplest version, white correlation in time. The model is defined in terms of two phenomenological parameters, denoted by λ and r_C. λ has the dimensions of a rate and sets the strength of the collapse. r_C is a correlation length which determines the spatial resolution of the collapse, the collapse is weak if the superposition size is much smaller than r_C, while becomes effective for delocalizations which are much larger than r_C. Different theoretical considerations lead to alternative choices for the parameters: Ghirardi, Rimini and Weber[3] proposed $\lambda = 10^{-17}\mathrm{s}^{-1}$ and $r_C = 10^{-7}\mathrm{m}$, Adler[30] proposed $\lambda = 10^{-8\pm2}\mathrm{s}^{-1}$ for $r_C = 10^{-7}\mathrm{m}$, and $\lambda = 10^{-6\pm2}\mathrm{s}^{-1}$ for $r_C = 10^{-6}\mathrm{m}$.

Roger Penrose argued[7,8] that when a system is found in a spatial quantum superposition, a corresponding superposition of two different space-times is generated. The superposition is unstable and decays in time. The more massive the system in the superposition, the larger the difference in the two space-times and the faster the wave-function collapse. The average collapse time τ would then be given by the expression $\tau \approx \hbar/E_g$, where $\hbar$ is the reduced Planck's constant and E_g is the gravitational self-energy of the difference between two (stationary) mass distributions of the superposition. Lajos Diósi developed a dynamical theory of gravity-related wave function collapse[1,2] which predicts the same form for the collapse time. Considered that the gravitational self-interaction energy diverges for point-like constituents, Diósi introduced[31] a minimum length R_0, which limits the spatial resolution of the mass density. E_g is then a function of R_0, the smaller R_0 the faster the collapse.

An unavoidable consequence of the dynamics of both the CSL and the gravity related collapse developed by Diósi, is that the non-linear interaction with the noise-filed induces a Brownian-like diffusion motion for the particles which, if charged, emits radiation. This phenomenon, which is not predicted in the context of QT, is usually called *spontaneous radiation*, and represents the observable which was investigated in our experimental surveys. The spontaneous radiation rate, due to the emission of protons in the atomic nuclei, was calculated in Refs.[26,27] and is given by:

$$\left.\frac{d\Gamma}{dE}\right|_t = N_{atoms} \cdot N_A^2 \cdot \frac{\hbar\, e^2}{4\,\pi^2\,\epsilon_0\, c^3\, m_0^2} \cdot \frac{\lambda}{r_C^2}\frac{1}{E}\,, \tag{1}$$

for the CSL model, and by:

$$\left.\frac{d\Gamma}{dE}\right|_t = N_{atoms} \cdot N_A^2 \cdot \frac{2}{3}\frac{G\, e^2}{\pi^{3/2}\,\epsilon_0\, c^3} \cdot \frac{1}{R_0^3 E}\,, \tag{2}$$

for the DP model. N_{atoms} is the number of atoms in the system with atomic number N_A, c is the speed of light, ϵ_0 is the vacuum permittivity, m_0 is the nucleon mass, G is the universal gravitational constant, E and t are the energy and the time. Electrons are relativistic in the energy range which was considered in our analyses, hence their contribution to the spontaneous radiation emission can not be considered.

The paper is organized as follows: in Section 2 the experimental apparatus is described, in Section 3 is given a brief description of the statistical analysis and the constraints on the characteristic parameters of the CSL and DP models are summarized, while concluding remarks and the future developments of our studies are outlined in Section 4.

2. The experimental setup

The experimental apparatus was based on a coaxial p-type High Purity Germanium detector (HPEGe) surrounded by multiple shielding layers: the inner shielding consisting of 5cm thick electrolytic copper, the external part of lead (30 cm from the bottom and 25 cm from the sides). Both the shielding and the cryogenic system were enclosed in an air tight steel housing, flushed with boil-off nitrogen, in order to suppress radon contamination (see Fig. 2 in Ref.[26] for a schematic representation of the setup, further details on the setup structure can be found in Ref.[26] and therein references). The experiment was operated in the extremely low background environment of the Gran Sasso underground National Laboratory of INFN in Italy.

The goal of the measurement was to disentangle a faint contribution of the spontaneous radiation emission process, to the measured spectrum, from environmental background. To this aim an accurate characterization of the whole apparatus was performed with a validated Monte Carlo (MC) code[32] based on the GEANT4 software library.[33]

The measured spectrum (corresponding to an exposure of 124 kg · day) is shown in black in Fig. 1, in the range $\Delta E = (1000 \div 3800)$keV (this is a reproduction of the original Fig. 1 in Ref.[27]). The energy range fulfills the theoretical requirements for the validity of the calculated rates (Eqs. (1) and (2)). In ΔE the main contribution to the background was found to be originated by residual radionuclides, present

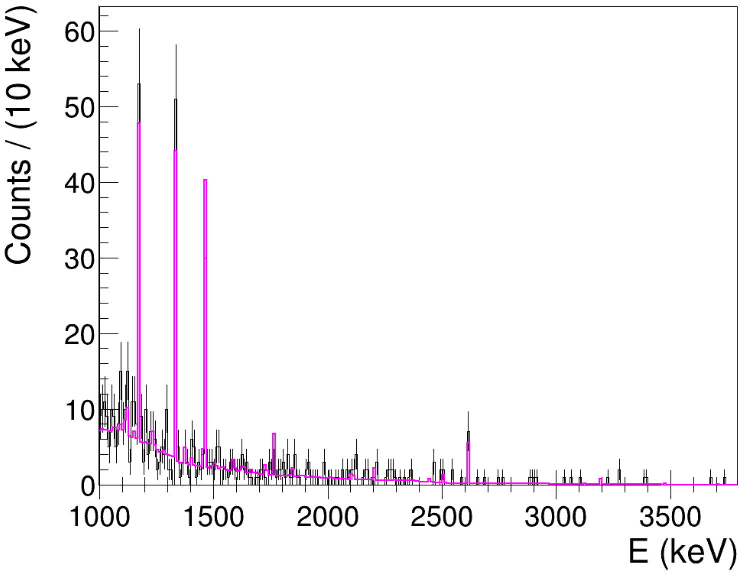

Fig. 1. The measured X-ray spectrum is shown in black in the selected energy range $\Delta E = (1000 - 3800)$ keV. The simulated background distribution is also shown in magenta.

in the materials of the setup, whose measured activities represented the inputs of the MC simulations. The magenta distribution in Fig. 1 represents the simulated background, 88% of the measured spectrum can be described in terms of known emission processes.

The simulation also allowed to compute the efficiencies, as a function of the energy, for the detection of spontaneously emitted photons in each component of the setup. To this end 10^8 photons, with uniform spatial distribution, were generated in each material in steps of 200 keV (i.e. 15 points in the ΔE). The efficiency functions $\epsilon_i(E)$ (i labelling the material of the detector) were then estimated by means of polynomial fits of the corresponding distributions, for each component of the detector which gives an appreciable contribution. The results of this analysis are summarized in Fig. 2 and Table 1 of Ref.[27].

3. Summary of the data analyses and results

The strategy of the Bayesian statistical analysis was to perform a comparison of the theoretically predicted spontaneous emission rate, generated by each component of the apparatus and weighted by the experimental efficiency and acceptance, with the measured distribution, accounting for the estimated background.

Given the calculated efficiency functions, and the theoretical rate (Eqs. (1) and (2)), the expected number of measured events, due to the spontaneous emission by protons belonging to the i-th material, during the acquisition time T is:

$$\int_{\Delta E} \left.\frac{d\Gamma}{dE}\right|_t T\,\epsilon_i(E)\,dE. \tag{3}$$

Summation over i yields the total expected signal contribution, which is a function of the phenomenological parameters (λ, r_C) or R_0, depending on the selected collapse model. The measured counts were assumed to fluctuate according to a Poissonian distribution and the probability density functions for the expected number of counts were derived, from which the following constraints on the models parameters were calculated, corresponding to a probability of 0.95:

$$\frac{\lambda}{r_C^2} < 52\,\mathrm{s}^{-1}\mathrm{m}^{-2}\,; \qquad R_0 > 0.54 \cdot 10^{-10}\mathrm{m}\,, \tag{4}$$

see Refs.[26, 27] for more details concerning the data analysis.

The first limit in Eq. (4) represents the stronger existing bound on the CSL model for values of the correlation length $r_C \leq 10^{-6}$m. The limit on R_0 (right side in Eq. (4)) is about three orders of magnitude stronger than previous bounds in the literature.[29] If R_0 is chosen as the size of the nucleus's wave function (as suggested by Penrose), our result is to be compared with the square-root of the mean square displacement of a nucleus in the lattice. For the Germanium crystal, cooled down at the liquid Nitrogen temperature, this would amount to an R_0 value of about $0.05 \cdot 10^{-10}$m, which is more than one order of magnitude less than the lower limit set by our experiment.

4. Conclusions and perspectives

We summarized the results of a dedicated measurement, performed at the Gran Sasso underground National Laboratory of INFN. The study was devoted to the search of spontaneous radiation emission, predicted by the CSL and the DP models of wave function collapse. We set the strongest bounds on the CSL phenomenological parameters in the region $r_C \leq 10^{-6}$m. Penrose's proposal for a gravity-related collapse of the wave function, in the present formulation, is ruled out. Our result indicates that the idea of gravity-related wave function collapse, which remains very appealing, will probably require a new approach. Indeed new theoretical developments are seeking for non-Markovian and/or dissipative versions of the collapse models, predicting a lower rate of spontanoeus radiation depending on the photon frequency. Both Penrose and Diósi are also pursuing the idea of a radiation free gravity-related collapse.

This pushes our efforts through further refinements our experimental techniques and data analyses methods. We are presently expanding our sensitive energy region from the MeV to few keV, with experimental setups based on Broad Energy Germanium detectors and ultra-radio pure targets. We are investigating the application of Machine Learning algorithms to identify the faint signal of the dynamical collapse, towards a deeper understanding of the foundations of Quantum Mechanics.

Acknowledgments

This publication was made possible through the support of Grant 62099 from the John Templeton Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation. We acknowledge support from the Foundational Questions Institute and Fetzer Franklin Fund, a donor advised fund of Silicon Valley Community Foundation (Grants No. FQXi-RFP-CPW-2008 and FQXi-MGB-2011), and from the H2020 FET TEQ (Grant No. 766900) and INFN (VIP). We thank the Austrian Science Foundation (FWF) which supports the VIP2 project with the grants P25529-N20, project P 30635-N36 and W1252-N27 (doctoral college particles and interactions). K. P. acknowledges support from the Centro Ricerche Enrico Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" (Open Problems in Quantum Mechanics project).

References

1. L. Diosi, A universal master equation for the gravitational violation of quantum mechanics, *Physics letters A* **120**, 377 (1987).
2. L. Diósi, Models for universal reduction of macroscopic quantum fluctuations, *Physical Review A* **40**, p. 1165 (1989).
3. G. C. Ghirardi, A. Rimini and T. Weber, Unified dynamics for microscopic and macroscopic systems, *Physical review D* **34**, p. 470 (1986).
4. P. Pearle, Combining stochastic dynamical state-vector reduction with spontaneous localization, *Physical Review A* **39**, p. 2277 (1989).
5. G. C. Ghirardi, P. Pearle and A. Rimini, Markov processes in hilbert space and continuous spontaneous localization of systems of identical particles, *Physical Review A* **42**, p. 78 (1990).
6. P. Pearle and E. Squires, Bound state excitation, nucleon decay experiments and models of wave function collapse, *Physical Review Letters* **73**, p. 1 (1994).
7. R. Penrose, On gravity's role in quantum state reduction, *Gen. Rel. Grav. 28: 581-600* (1996).
8. R. Penrose, On the gravitization of quantum mechanics 1: Quantum state reduction, *Foundations of Physics 44, 557-575* (2014).
9. A. Bassi and G. Ghirardi, Dynamical reduction models, *Physics Reports* **379**, 257 (2003).
10. T. Kovachy, P. Asenbaum, C. Overstreet, C. Donnelly, S. Dickerson, A. Sugarbaker, J. Hogan and M. Kasevich, Quantum superposition at the half-metre scale, *Nature* **528**, 530 (2015).
11. S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor and J. Tüxen, Matter–wave interference of particles selected from a molecular library with masses exceeding 10000 amu, *Physical Chemistry Chemical Physics* **15**, 14696 (2013).
12. M. Toroš and A. Bassi, Bounds on quantum collapse models from matter-wave interferometry: calculational details, *Journal of Physics A: Mathematical and Theoretical* **51**, p. 115302 (2018).
13. K. C. Lee, M. R. Sprague, B. J. Sussman, J. Nunn, N. K. Langford, X.-M. Jin, T. Champion, P. Michelberger, K. F. Reim, D. England *et al.*, Entangling macroscopic diamonds at room temperature, *Science* **334**, 1253 (2011).

14. S. Belli, R. Bonsignori, G. D'Auria, L. Fant, M. Martini, S. Peirone, S. Donadi and A. Bassi, Entangling macroscopic diamonds at room temperature: Bounds on the continuous-spontaneous-localization parameters, *Physical Review A* **94**, p. 012108 (2016).
15. T. Kovachy, J. M. Hogan, A. Sugarbaker, S. M. Dickerson, C. A. Donnelly, C. Overstreet and M. A. Kasevich, Matter wave lensing to picokelvin temperatures, *Physical review letters* **114**, p. 143004 (2015).
16. A. Vinante, R. Mezzena, P. Falferi, M. Carlesso and A. Bassi, Improved noninterferometric test of collapse models using ultracold cantilevers, *Physical review letters* **119**, p. 110401 (2017).
17. O. Usenko, A. Vinante, G. Wijts and T. Oosterkamp, A superconducting quantum interference device based read-out of a subattonewton force sensor operating at millikelvin temperatures, *Applied Physics Letters* **98**, p. 133105 (2011).
18. A. Vinante, A. Collaboration *et al.*, Present performance and future upgrades of the auriga capacitive readout, *Classical and Quantum Gravity* **23**, p. S103 (2006).
19. B. P. Abbott, R. Abbott, T. Abbott, M. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. Adhikari *et al.*, Gw150914: The advanced ligo detectors in the era of first discoveries, *Physical review letters* **116**, p. 131103 (2016).
20. B. P. Abbott, R. Abbott, T. Abbott, M. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. Adhikari *et al.*, Observation of gravitational waves from a binary black hole merger, *Physical review letters* **116**, p. 061102 (2016).
21. M. Armano, H. Audley, G. Auger, J. Baird, M. Bassan, P. Binetruy, M. Born, D. Bortoluzzi, N. Brandt, M. Caleno *et al.*, Sub-femto-g free fall for space-based gravitational wave observatories: Lisa pathfinder results, *Physical review letters* **116**, p. 231101 (2016).
22. M. Armano, H. Audley, J. Baird, P. Binetruy, M. Born, D. Bortoluzzi, E. Castelli, A. Cavalleri, A. Cesarini, A. Cruise *et al.*, Beyond the required lisa free-fall performance: New lisa pathfinder results down to 20 μ hz, *Physical review letters* **120**, p. 061101 (2018).
23. S. L. Adler and A. Vinante, Bulk heating effects as tests for collapse models, *Physical Review A* **97**, p. 052119 (2018).
24. M. Bahrami, Testing collapse models by a thermometer, *Physical Review A* **97**, p. 052118 (2018).
25. K. Piscicchia, A. Bassi, C. Curceanu, R. D. Grande, S. Donadi, B. C. Hiesmayr and A. Pichler, CSL collapse model mapped with the spontaneous radiation, *Entropy* **19**, p. 319 (2017).
26. S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, Underground test of gravity-related wave function collapse, *Nature Physics* **17**, 74 (2021).
27. S. Donadi, K. Piscicchia, R. Del Grande, C. Curceanu, M. Laubenstein and A. Bassi, Novel CSL bounds from the noise-induced radiation emission from atoms, *The European Physical Journal C* **81**, 1 (2021).
28. M. Carlesso, A. Bassi, P. Falferi and A. Vinante, Experimental bounds on collapse models from gravitational wave detectors, *Physical Review D* **94**, p. 124036 (2016).
29. B. Helou, B. Slagmolen, D. E. McClelland and Y. Chen, Lisa pathfinder appreciably constrains collapse models, *Physical Review D* **95**, p. 084054 (2017).
30. S. L. Adler, Lower and upper bounds on csl parameters from latent image formation and IGM heating, *Journal of Physics A: Mathematical and Theoretical* **40**, p. 2935 (2007).
31. L. Diósi, Notes on certain newton gravity mechanisms of wave function localization and decoherence, *J. Phys. A 40, 2989-2995* (2007).

32. M. Boswell, Y.-D. Chan, J. A. Detwiler, P. Finnerty, R. Henning, V. M. Gehman, R. A. Johnson, D. V. Jordan, K. Kazkaz, M. Knapp *et al.*, MaGe-a Geant4-based Monte Carlo application framework for low-background germanium experiments, *IEEE Transactions on Nuclear Science* **58**, 1212 (2011).
33. S. Agostinelli, J. Allison, K. a. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand *et al.*, Geant4—A simulation toolkit, *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **506**, 250 (2003).