Investigating Quantum Collapse with the VIP experiment at LNGS

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Testing Quantum Mechanics Underground

LNGS, 20 March 2025

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QT & Collapse models

But … What's the problem?

"The Copenhagen interpretation assumes a mysterious division between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics. During measurement the state vector of the microscopic system collapses in a probabilistic way to one of a number of classical states, in a way that is unexplained, and cannot be described by the time-dependent Schrödinger equation."

Weinberg [Phys. Rev. A 85, 062116 (2012)]

QT & Collapse models

Axioms of QM:

1) every physical system is associated to a Hilbet space, observables are self-adjoint operators, possible measurement outcomes are:

$$O\,|o_n\rangle = o_n\,|o_n\rangle$$

2) time evolution is governed by the Schördinger equation :

$$i\hbar\frac{d}{dt}|\psi(t)\rangle = H\,|\psi(t)\rangle$$

3) probability of getting a measurement outcome o_n at time t :

$$P[o_n] = |\langle o_n|\psi(t)\rangle|^2$$

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first order in t → deterministic

$$|\psi(t)\rangle = U(t,t_0)\,|\psi(t_0)\rangle$$

linear →
superposition principle

3) probability of getting a measurement outcome o_n at time t :

$$P[o_n] = |\langle o_n|\psi(t)\rangle|^2$$

4) wavepacket reduction principle (WPR):

$$|\psi(t)\rangle \text{ before measurement} \longrightarrow |o_n\rangle \text{ after measurement}$$

genuinely probabilistic, stochastic

non-linear

QT & Collapse models

von Neumann scheme for an ideal measurement process:

- Microscopic system S, observable O (assume, for simplicity, its spectrum is purely discrete and non–degenerate). M is the apparatus devised to measure the observable O of the microsystem S.

- M has a ready–state $|A_0\rangle$ plus a set of mutually orthogonal states $|A_n\rangle$ corresponding to different macroscopic configurations of the instrument (different positions of a pointer along a scale.

- Assume that the interaction between the microsystem S and the apparatus M is linear (universal validity of Shr. eq.)and yields a perfect correlation between the initial state of S and the final state of the apparatus, i.e.

$$\text{Initial state:} \quad |o_n\rangle \otimes |A_0\rangle \qquad \longrightarrow \qquad \text{Final state:} \quad |o_n\rangle \otimes |A_n\rangle$$

If the initial state of the micro-system is $|m+l\rangle \;=\; \frac{1}{\sqrt{2}}[|o_m\rangle + |o_l\rangle]$

the final state of the micro-system + apparatus is entangled

$$\begin{aligned} |m+l\rangle \otimes |A_0\rangle &= \frac{1}{\sqrt{2}}\left[|o_m\rangle + |o_l\rangle\right] \otimes |A_0\rangle \longrightarrow \\ &\longrightarrow \frac{1}{\sqrt{2}}\left[|o_m\rangle \otimes |A_m\rangle + |o_l\rangle \otimes |A_l\rangle\right] \end{aligned}$$

QT & Collapse models

von Neumann scheme for an ideal measurement process:

- standard way out is WRP, at the end of the measurement process the final vector

$$|m+l\rangle \otimes |A_0\rangle = \frac{1}{\sqrt{2}}\left[|o_m\rangle + |o_l\rangle\right] \otimes |A_0\rangle \longrightarrow$$
$$\longrightarrow \frac{1}{\sqrt{2}}\left[|o_m\rangle \otimes |A_m\rangle + |o_l\rangle \otimes |A_l\rangle\right]$$

reduces to one of its terms (with probabilities ½ for both cases):

$$|o_m\rangle \otimes |A_m\rangle \quad \text{or} \quad |o_l\rangle \otimes |A_l\rangle$$

One has to accept that:

- QM incorporates two dynamical principles: a) evolution governed by Schrödinger equation (unitary, linear) b) measurement process governed by WPR (stochastic, nonlinear),

- QM does not tell where the linear Hamiltonian evolution has to be suspended and WRP takes place.

QT & Collapse models

- A quantum system evolves according to the Schrödinger equation, possibly being superimposed, when left alone. Then, when measured it randomly collapses.
- So far so good, phenomenologically: the two situations are different—in the first case the system is isolated, in the second case it interacts with the measuring device.
- BUT QT is not supposed to be a phenomenological theory, but a fundamental description of nature.

If those mentioned are the rules of a fundamental theory, then there is a fundamental distinction (a property of nature) among the quantum system and the measuring device!!

But the measuring device is made of atoms, which are quantum (cat paradox Schrödinger, 1935).

QT & Collapse models

Among the proposed wayouts : Bohmian Mechanics (Dürr & Teufel, 2009), Many Worlds Interpretation (Wallace, 2012), the Consistent Histories Approach (Griffiths, 2003) and the Modal Interpretation (Dieks & Vermaas, 1998),

dynamical (spontaneous) collapse incorporates (at least phenomenologically) in the Schrödinger dynamics non-linearity and stochasticity which localize the wave function in space:

In the microscopic world particles tend to dissolve in space, under the effect of the Schrödinger dynamics. "But when particles interact with each other, the collapse terms make them stiffer and stiffer, to the point that when a macroscopic number of them glues together to form a table or a chair, they become rigid." (Bassi 2021)

Models of w.f. dynamical reduction

But what triggers the w.f. Collapse?

- CSL introduce a scale, setting the emergence of classicality, through a mathematically consistent, phenomenological, modification of the QT,

- wave function collapse is related to gravitational decoherence Diosi-Penrose (DP).

Feynman in lectures on gravitation: breakdown of the quantum superposition at macroscopic scale, possibility that gravity might not be quantized.

Space-time uncertainty destroys quantum coherence

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Global time uncertainty and decoherence

Diosi, L. (2005), Braz. J. Phys. 35, 260, Diosi, L., and B. Lukacs (1987), Annalen der Physik 44, 488, Diosi, L. (1987), Physics Letters A 120, 377, A. Bassi et al.,Rev. Mod. Phys. 85,471

Initial state of a quantum system is a superposition of two eigenstates of total Hamiltonian

$$|\psi\rangle = c_1|\varphi_1\rangle + c_2|\varphi_2\rangle$$

time evolution

$$|\psi(t)\rangle = c_1 \exp(-i\hbar^{-1}E_1 t)|\varphi_1\rangle + c_2 \exp(i\hbar^{-1}E_2 t)|\varphi_2\rangle$$

Let us add an uncertainty to the time $t \to t + \delta t$

and assume that is distributed Gaussian, with zero mean, and dispersion which is proportional to the mean time, $\mathbf{M}[(\delta t)^2] = \tau t$ then the density matrix evolves as:

$$\begin{aligned}
&\rho(t) \equiv \mathbf{M}\left[|\psi(t)\rangle\langle\psi(t)|\right] = \\
= \;& |c_1|^2|\varphi_1\rangle\langle\varphi_1| + |c_2|^2|\varphi_2\rangle\langle\varphi_2| + \\
+ \;& \{c_1^\star c_2 \exp(i\hbar^{-1}\Delta E t)\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E \delta t)\right]|\varphi_2\rangle\langle\varphi_1| + \\
+ \;& \quad \text{h.c.} \quad \} \,.
\end{aligned}$$

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$$\begin{aligned} &\rho(t) \equiv \mathbf{M}[|\psi(t)\rangle\langle\psi(t)|] = \\ &= |c_1|^2|\varphi_1\rangle\langle\varphi_1| + |c_2|^2|\varphi_2\rangle\langle\varphi_2| + \\ &\cancel{+ \{c_1^\dagger c_2 \exp(i\hbar^{-1}\Delta E t)\mathbf{M}[\exp(i\hbar^{-1}\Delta E\delta t)]|\varphi_2\rangle\langle\varphi_1| +} \\ &\cancel{+ \quad \text{h.c.} \quad \}} . \end{aligned}$$

$$\boxed{\begin{gathered} \mathbf{M}[\exp(i\hbar^{-1}\Delta E\delta t)] = e^{-t/t_D} \\ t_D = \frac{\hbar^2}{\tau}\frac{1}{(\Delta E)^2} \end{gathered}}$$

Global time uncertainty and decoherence

The time evolution for the density matrix

$$\hat{\rho}(t+\tau)=\exp\left[\frac{-i\hat{H}\tau}{\hbar}\right]\hat{\rho}(t)\exp\left[\frac{i\hat{H}\tau}{\hbar}\right]$$

Described by the von Neumann equation

$$\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]$$

turns to

$$\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]-\frac{1}{2}\tau\hbar^{-2}[H,[H,\rho]]$$

G. J. Milburn Prys. Rev. A 44 5401 (1991)

Local time uncertainty and decoherence

To generalize the concept for a local time $t_{\mathbf{r}} \to t + \delta t_{\mathbf{r}}$

one defines the correlation $\mathbf{M}[\delta t_{\mathbf{r}} \delta t_{\mathbf{r}'}] = \tau_{\mathbf{r}\mathbf{r}'} t$

Galileo invariant spatial correlation function

If the total Hamiltonian is decomposed in the sum of the local ones

$$\frac{d\rho}{dt} = -i\hbar^{-1}[H, \rho] - \frac{1}{2}\hbar^{-2} \sum_{\mathbf{r},\mathbf{r}'} \tau_{\mathbf{r}\mathbf{r}'} [H_{\mathbf{r}}, [H_{\mathbf{r}'}, \rho]]$$

The master equation suppresses superpositions of eigenstates of local energy

local time uncertainty and gravity

Local time fluctuation is related to a fluctuation of the local gravitational potential

$$\delta t_{\mathbf{r}} \equiv \delta \int_0^t dt' g_{00}^{1/2}(\mathbf{r},t') \approx -c^{-2} \int_0^t dt' \Phi(\mathbf{r},t')$$

Hence the crucial point: it is assumed that the gravitational potential should not be quantized

BUT that QM requires an absolute indeterminacy of the gravitational field.

I.E. the gravitational potential is a c-number stochastic variable, whose mean value is to be identified with the classical Newtonian potential.

.. so one remains with finding the correlations of local uncertainties of Newtonian gravity

Can the gravitational field be measured with unlimited precision?

Diosi and Lukacs [Ann. Phys. 44, 488 (1987)] apply the arguments of [N. Bohr and L. Rosenfeld, K. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 12, 1 (1933)] answer NO

$$< \phi(\mathbf{r},t) > = \phi_N(\mathbf{r},t)$$

$$< \phi(\mathbf{r},t)\,\phi(\mathbf{r}',t') > - < \phi(\mathbf{r},t) > < \phi(\mathbf{r}',t') > \sim \frac{\hbar G}{|\mathbf{r}-\mathbf{r}'|}\,\delta(t-t')$$

Going back to the searched correlation of the local time fluctuation $\mathbf{M}[\delta t_{\mathbf{r}} \delta t_{\mathbf{r}'}] = \tau_{\mathbf{r}\mathbf{r}'} t$

$$\delta t_{\mathbf{r}} \equiv \delta \int_0^t dt' g_{00}^{1/2}(\mathbf{r},t') \approx -c^{-2} \int_0^t dt' \Phi(\mathbf{r},t') \longrightarrow \tau_{\mathbf{r}\mathbf{r}'} = \mathrm{const} \times \frac{G\hbar}{|\mathbf{r}-\mathbf{r}'|} c^{-4}$$

Master equation

$$\tau_{\mathbf{rr}'} = \text{const} \times \frac{G\hbar}{|\mathbf{r}-\mathbf{r}'|} c^{-4}$$

the local time correlation is extremely small

substituted in the master equation

$$\frac{d\rho}{dt} = -i\hbar^{-1}[H,\rho] - \frac{1}{2}\hbar^{-2}\sum_{\mathbf{r},\mathbf{r}'}\tau_{\mathbf{rr}'}[H_{\mathbf{r}},[H_{\mathbf{r}'},\rho]]$$

yields

$$\frac{d\rho}{dt} = - i\hbar^{-1}[H,\rho] - \frac{G}{2}\hbar^{-1}\int\int\frac{d\mathbf{r}d\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}[f(\mathbf{r}),[f(\mathbf{r}'),\rho]]$$

With $H_r = c^2 f(r)$ (f is the local mass density operator)

Master equation

Denote the configuration coordinates (classical and spin) of the dynamical system by X. The corresponding mass density at the point r is $f(\mathbf{r}|X)$

Given the coordinate eigenstate |x> we have $f(\boldsymbol{r}|X)\delta(X'-X) \equiv \langle X'|\hat{f}(\boldsymbol{r})|X\rangle$

So if one introduces the damping time:

$$[\tau_d(X,X')]^{-1} = \frac{G}{2\hbar}\int\int d^3r\, d^3r' \times \frac{[f(\mathbf{r}|X)-f(\mathbf{r}|X')][f(\mathbf{r}'|X)-f(\mathbf{r}'|X')]}{|\mathbf{r}-\mathbf{r}'|}$$

the master equation becomes

$$\langle X|\dot{\hat{\rho}}(t)|X'\rangle = (-\mathrm{i}/\hbar)\langle X|[\hat{H}_0,\hat{\rho}(t)]|X'\rangle - [\tau_d(X,X')]^{-1}\langle X|\hat{\rho}(t)|X'\rangle\ .$$

Energy decoherence

$$\langle X|\dot{\hat\rho}(t)|X'\rangle = (-i/\hbar)\langle X|[\hat H_0, \hat\rho(t)]|X'\rangle$$
$$\boxed{-[\tau_d(X,X')]^{-1}\langle X|\hat\rho(t)|X'\rangle\ .}$$

$$[\tau_d(X,X')]^{-1} = \frac{G}{2\hbar}\int\int d^3r\, d^3r' \times \frac{[f(\mathbf{r}|X) - f(\mathbf{r}|X')][f(\mathbf{r}'|X) - f(\mathbf{r}'|X')]}{|\mathbf{r}-\mathbf{r}'|}$$

If the difference between the mass distributions of two states |X> and |X'> in superposition becomes big

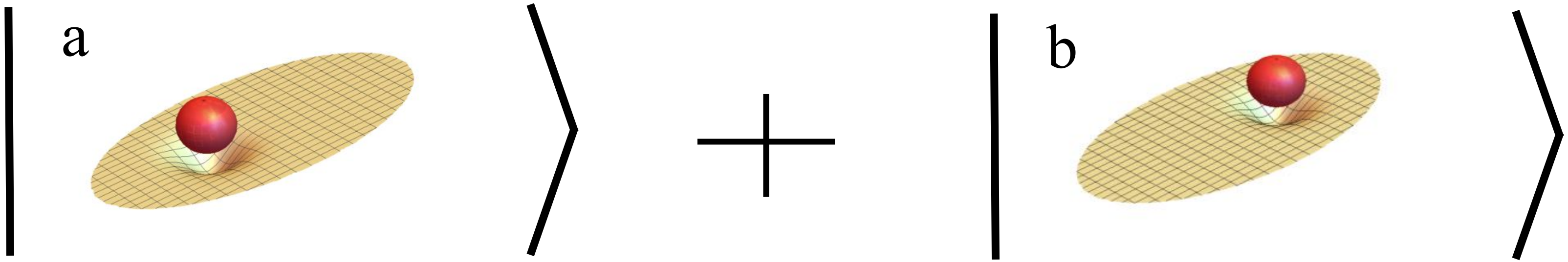
the corresponding damping time becomes short

the corresponding off-diagonal terms of the density operator vanish

this QM violating phenomenon is ENERGY DECOHERENCE

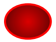
in Diosi-Penrose approach.

Gravity induced collapse



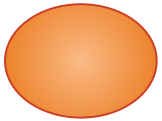
$$\Delta E_{\rm DP} = 4\pi G \int d\boldsymbol{r} \int d\boldsymbol{r}' \frac{[\mu_a(\boldsymbol{r}) - \mu_b(\boldsymbol{r})]\,[\mu_a(\boldsymbol{r}') - \mu_b(\boldsymbol{r}')]}{|\boldsymbol{r} - \boldsymbol{r}'|}.$$

$$\tau_{\rm DP} = \frac{\hbar}{\Delta E_{\rm DP}}$$



Proton: m ≃ 10^{-27} Kg, R ≃ 10^{-15} m

$\tau_{\rm DP} \simeq 10^{6}$ years



Dust grain: m ≃ 10^{-12} Kg, R ≃ 10^{-5} m

$\tau_{\rm DP} \simeq 10^{-8}$ s

Gravity induced collapse

The DP theory is parameter-free, but the gravitational self energy difference diverges for point-like particles -> a short-length cutoff R_0 is introduced to regularize the theory.

Diósi: minimum length R_0 limits the spatial resolution of the mass density, a short-length cutoff to regularize the mass density.

Penrose: solution of the stationary Shroedinger-Newton equation, with R_0 the size of the particle mass density $\mu(\boldsymbol{r}) = m|\psi(\boldsymbol{r}, t)|^2$

ΔE_{DP} becomes a function of R_0 the larger R_0 the longer the collapse time, the fainter the spontaneous radiation

The CSL model

$$d|\psi_t\rangle = \Big[\underbrace{-\frac{i}{\hbar}H dt}_{\text{System's Hamiltonian}} + \underbrace{\sqrt{\lambda}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt}_{\text{NEW COLLAPSE TERMS}}\Big]|\psi_t\rangle$$

System's Hamiltonian

NEW COLLAPSE TERMS → **New Physics**

$N(\mathbf{x}) = a^\dagger(\mathbf{x})a(\mathbf{x})$ particle density operator — **choice of the preferred basis**

$\langle N(\mathbf{x})\rangle_t = \langle \psi_t|N(\mathbf{x})|\psi_t\rangle$ — **nonlinearity**

$W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[W_t(\mathbf{x})] = 0, \quad \mathbb{E}[W_t(\mathbf{x})W_s(\mathbf{y})] = \delta(t-s)e^{-(\alpha/4)(\mathbf{x}-\mathbf{y})^2}$ — **stochasticity**

$\lambda =$ collapse strength $\qquad r_C = 1/\sqrt{\alpha} =$ correlation length — **two parameters**

G. C. Ghirardi, A. Rimini, and T. Weber, Physical Review D 34, 470 (1986).
P. Pearle, Phys. Rev. A39, 2277 (1989)
G. C. Ghirardi, P. Pearle, and A. Rimini, Phys. Rev. A 42, 78 (1990)
A. Bassi and G. C. Ghirardi 2003 Dynamical reduction models Phys. Rep. 379 257

the smaller λ/r_C^2 the fainter the spontaneous radiation

What is spontaneous radiation?

Direct tests: creating a large superposition of a massive system, to guarantee that decay time is short enough for the collapse to become effective before any kind of external noise disrupts the measurement, matter-wave interferometry with macromolecules, phononic states, experiments in space: no gravity ---> more time (MAQRO, CAL, etc..).

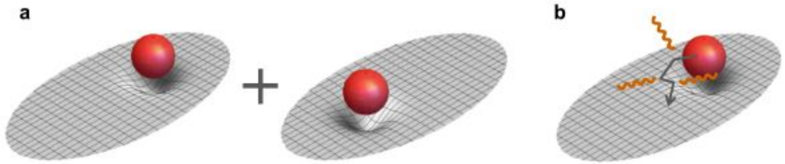
Kovachy, T. et al. Quantum superposition at the half-metre scale. Nature 528, 530–533 (2015). Fein, Y. Y. et al. Quantum superposition of molecules beyond 25 kDa. Nature Physics 15, 1242–1245 (2019). Lee, K. C. et al. Entangling macroscopic diamonds at room temperature. Science 334, 1253–1256 (2011).

Angelo Bassi, Kinjalk Lochan, Seema Satin, Tejinder P. Singh, Hendrik Ulbricht, Rev. Mod. Phys. 85, 471-527 (2013).

We use an indirect signature of the collapse: spontaneous radiation

Testing collapse models by means of Gamma ray spectroscopy

Unavoidable side effect of the collapse:
a Brownian-like diffusion of the system in space.



Collapse probability is Poissonian in t -> Lindblad dynamics for the statistical operator -> free particle average square momentum increases in time.

A recent general result, see S. Donadi, L. Ferialdi, A. Bassi, "Collapse dynamics are diffusive"
Phys. Rev. Lett. 130, 230202 (2023)

Then charged particles emit spontaneous radiation.

Spontaneous emission in the γ-rays regime

- *CSL - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{CSL} = \frac{\hbar\lambda}{4\pi^2\epsilon_0 c^3 r_C^2 m_0^2 E}(N_p^2 + Ne)$$

- *DP - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{DP} = \frac{G}{12\pi^{3/2}\epsilon_0 c^3 R_0^3 E}\{N_p^2 + N_e\}$$

the photon w.l. λ_γ is intermediate between the nuclear dimension and the lower atomic orbit radius -> protons emit coherently, electrons emit independently

λ - *collapse strength*

r_C - *correlation length*

see e. g. S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

R_0 - *size of the particle mass density. See e.g. Diósi, L. J. Phys. Conf. Ser. 442, 012001 (2013)., Penrose, R. Found. Phys. 44, 557–575 (2014).*

The experimental setup (M. Laubenstein)

The experimental apparatus is based on a coaxial p-type high purity germanium detector (HPGe):

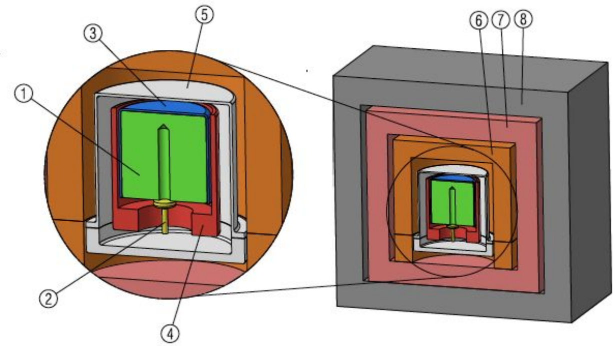
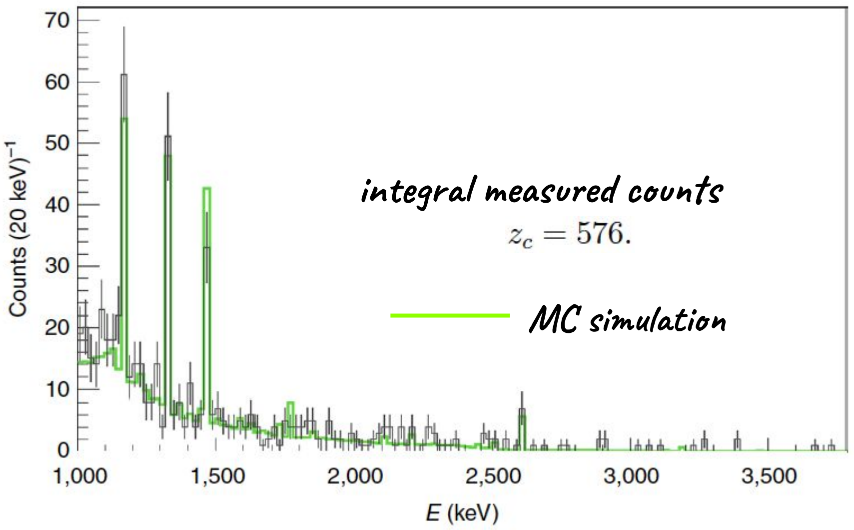


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

- Exposure 124 kg · day, $m_{Ge} \sim 2$kg
- passive shielding: inner - electrolytic copper, outer - lead
- on the bottom and on the sides 5 cm thick borated polyethylene plates give a partial reduction of the neutron flux
- an airtight steel housing encloses the shield and the cryostat, flushed with boil-off nitrogen to minimize the presence of radon.

Measured spectrum and background simulation

The experimental apparatus is characterised, through a validated MC code, based on the GEANT-4 software library. The background is due to emission of residual radio-nuclides:



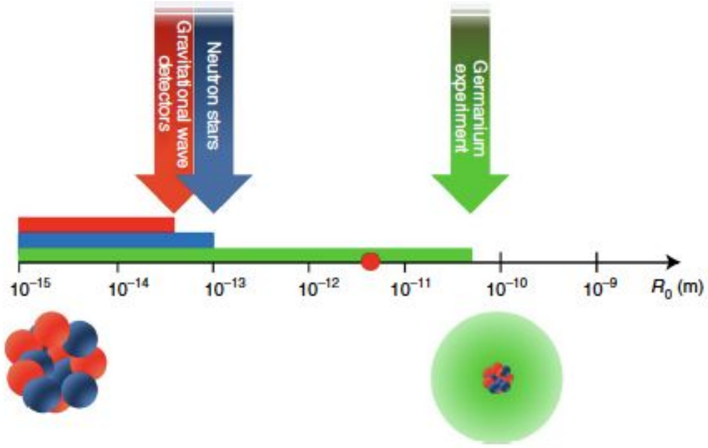
- the activities are measured for each component
- the MC simulation accounts for:

1. emission probabilities and decay schemes for each radio-nuclide in each material
1. photons propagation and interactions
2. detection efficiencies.

The simulation describes 88% of the integral counts:

$$z_{b,ij} = \frac{m_i\, A_{ij}\, T\, N_{rec,ij}}{N_{ij}}, \qquad z_b = \sum_{i,j} z_{b,ij} = 506.$$

Lower bound on R_0



EXPERIMENTAL : $R_0 > 0.54 \cdot 10^{-10}$ m

If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to compare the limit with the properties of nuclei in matter.

In a crystal $R^2_0 = \langle u^2 \rangle$ is the mean square displacement of a nucleus in the lattice, which, for the germanium crystal, cooled to liquid nitrogen temperature amounts to:

THEORETICAL EXPECTATION $R_0 = 0.05 \cdot 10^{-10}$ m

"Underground test of gravity-related wave function collapse". Nature Physics 17, pages 74–78 (2021)

The future of Gravity-related collapse

Penrose proposal is rouled out in present formulation!

ways out .. generalized models e.g. :

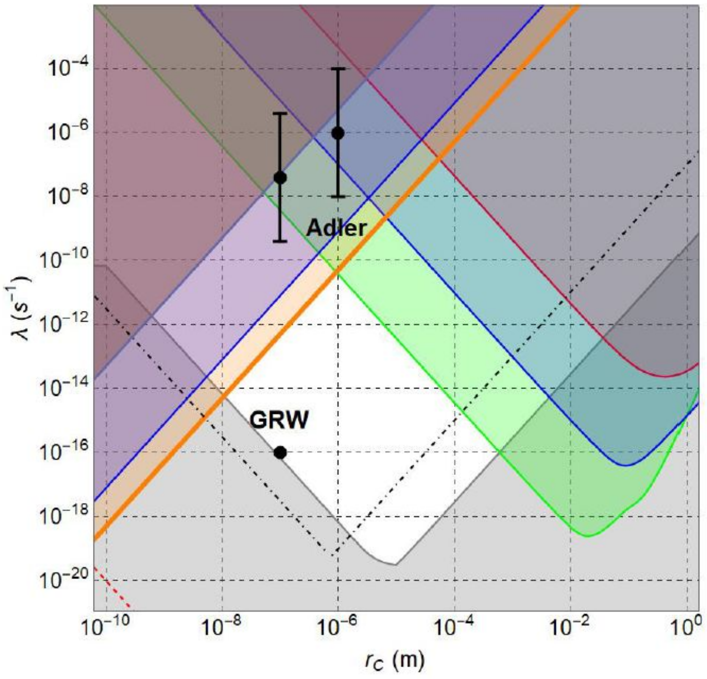
- add dissipation terms to the master equation and stochastic nonlinear Schroedinger equation of the DP theory, to counteract the runaway energy increase,
- non-Markovian correlation function.

$$< \phi(\mathbf{r},t)\,\phi(\mathbf{r}',t') > - < \phi(\mathbf{r},t) >< \phi(\mathbf{r}',t') > \sim \frac{\hbar G}{|\mathbf{r}-\mathbf{r}'|}\,\cancel{\delta(t-t')}$$

complex dependence of the S. E. on energy and on the atomic structure is to be considered!

Constraints on the CSL

Similar analysis leads to bounds on the strength and correlation length of the CSL
(Eur. Phys. J. C (2021) 81: 773)



$\lambda/r_C^2 < 52\ m^{-2}\ s^{-1}$

Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 µm (about the smallest possible size detectable by human eye) collapses in less than 0.01 s (about the time resolution of human eye) [31]. Contrary to the bounds set by experiments, the theoretical bound has a subjective component, since it depends on which systems are considered as "macroscopic". For example, it was previously suggested that the collapse should be strong enough to guarantee that a carbon sphere with the diameter of 4000 Å should collapse in less than 0.01 s, in which case the theoretical bound is given by the dash-dotted black line [36]. A much weaker theoretical bound was proposed by Feldmann and Tumulka, by requiring the ink molecules corresponding to a digit in a printout to collapse in less than 0.5 s (red line in the bottom left part of the exclusion plot, the rest of the bound is not visible as it involves much smaller values of λ than those plotted here) [37]. The right part of the parameter space is excluded by the bounds coming from the study of gravitational waves detectors: Auriga (red), Ligo (Blue) and Lisa-Pathfinder (Green) [30]. On the left part of the parameter space there is the bound from the study of the expansion of a Bose–Einstein condensate (red) [28] and the most recent from the study of radiation emission from Germanium (purple) [22]. This bound is improved by a factor 13 by this analysis performed here, with a confidence level of 0.95, and it is shown in orange

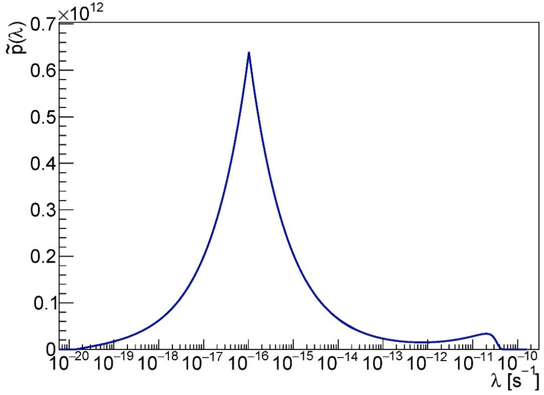
First separate determination of pdfs for λ and r_C

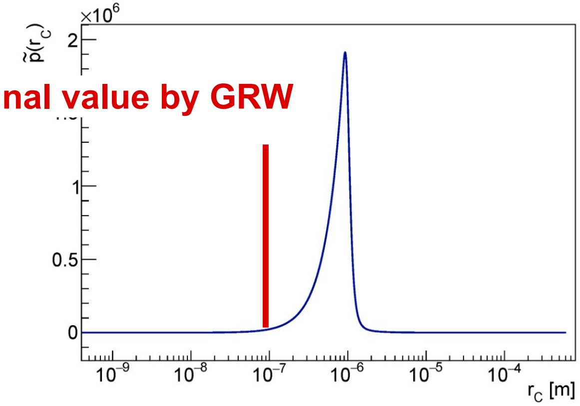
Entropy 2023, 25(2), 295

- Experimental studies of the spontaneous radiation phenomenon focused so far on the λ/r_C^2 ratio, which regulates the predicted yield -> allow to exclude regions of the (λ–r_C) parameter space.

- Combined information from theoretical considerations and other experiments has led to the further exclusion of sectors of the (λ–r_C) plane, characterized by a different functional relation between λ and r_C.

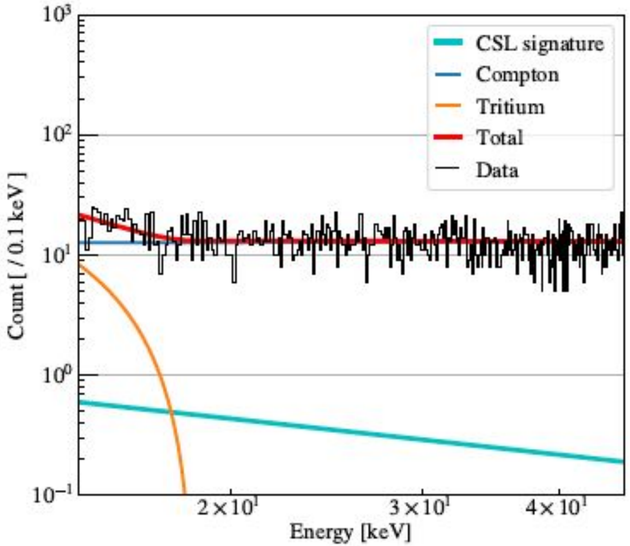
- Including this rich prior information in the statistical analysis permits to disentangle the two parameters' probability density functions:





What happens in the X-rays regime?

MAJORANA DEMONSTRATOR explored this range using the high energy predicted rate - PHYS. REV. LETT. 129, 080401 (2022)



Higher exposure

↓

limit on DP

$R_0 > 2.54 \pm 0.03 \cdot 10^{10}$ m

BUT

In this range

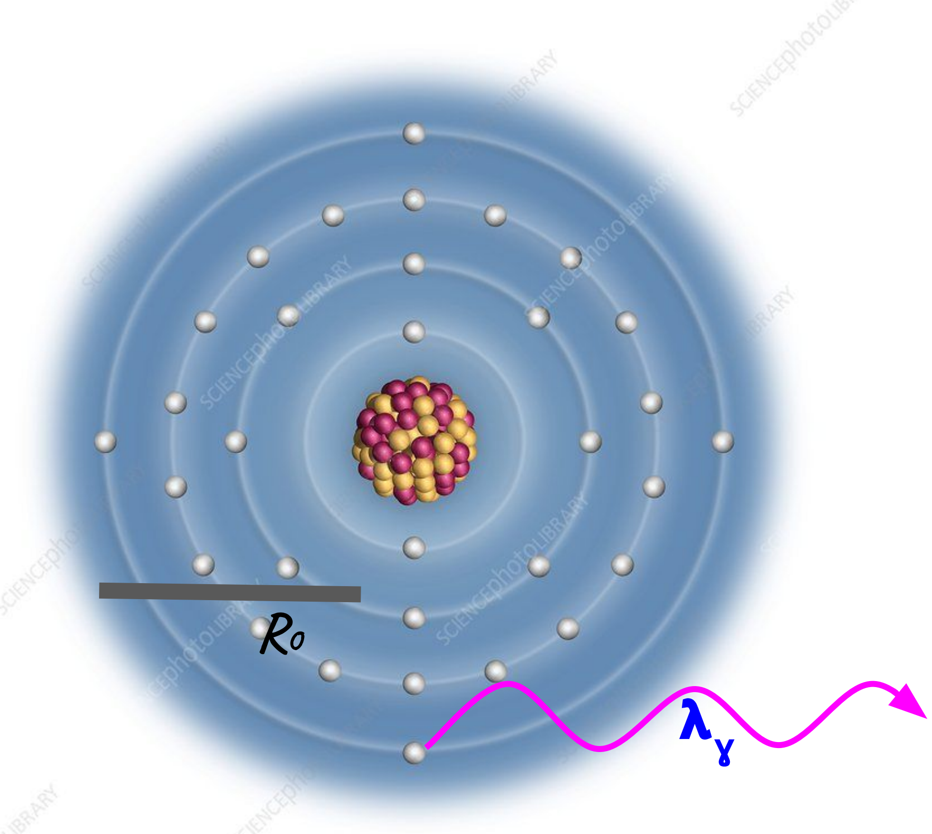
S.E. from protons

and electrons

cancels !!

Spontaneous emission in the X-rays regime

In the low-energy regime, the photon w.l. is comparable to the atomic orbits dimensions



e.g. $\lambda_{dB}(E=15\ keV) = 0.8\ A$

$r_{1s} = 0.025\ A$; $r_{4p} = 1.5\ A$

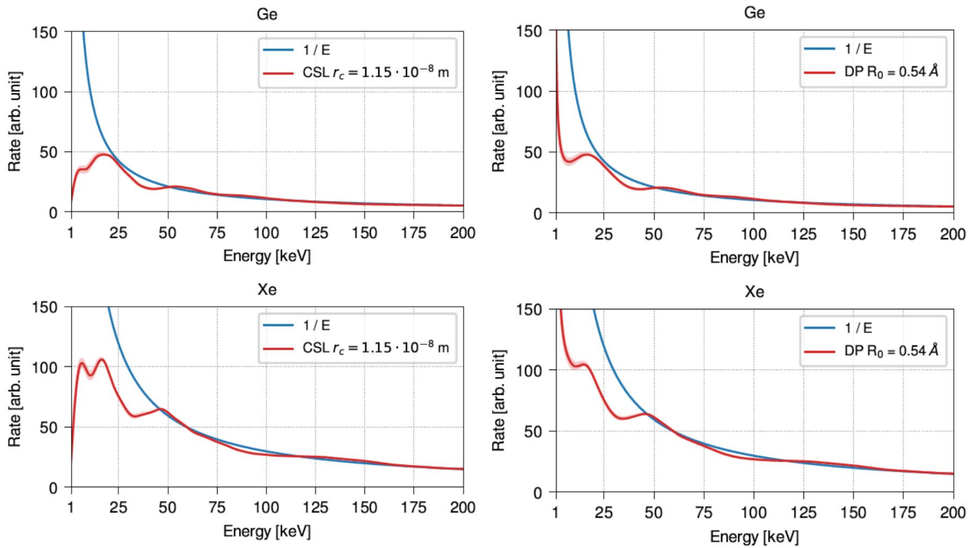
When the correlation length (R_0) of the model is of the order of the atomic dymension, and also λ_γ is of the order of the mean atomic radii:

- electrons start to emit coherently (QUADRATICALLY)
- BUT electrons-protons contribution START TO CANCEL

What's next?

We developed the first model which predicts a characteristic spontaneous E. M. radiation distinctive of the decoherence mechanism:

K. P. et al., Phys. Rev. Lett. 132, 250203 (2024)



Spontaneous radiation rate for the CSL model (left) and DP (right) calculated for a Ge atom (top panels) and a Xe atom (bottom panels). In blue the approximated theory.

- **The energy spectrum of this radiation is influenced by the atomic structure of the emitter.**
- **The spontaneous radiation rate, within the range of (1-15) keV, is unique to the specific decoherence mechanism.**

VIP - towards testing unified theories of quantum & gravity

<u>Continuous Spontaneous Localization</u> (CSL) & <u>Diosi-Penrose</u> (DP)

<u>STRONG CONNECTION WITH QG:</u>

Spontaneous decoherence induced by space-time uncertainty

&

Irreversibility in Quantum Gravity/Cosmology at the Planck scale

lead to the same structure of master equations

L. Diosi (2023) J. Phys.: Conf. Ser. 2533 012005)

Physical Review X, 13(4):041040, 2023, J. Phys. A, 57:395303, 2024, Nat. Comm. 12, 4449 (2021)

this <u>spectacular connection</u> points toward a <u>potential reconciliation between quantum mechanics and gravity</u>

can be tested with VIP

What's next?

Based on the R&D activity with a BEGe based setup we are studying a <u>dedicated setup to investigate unified theories of Quantum and Gravity with a simultaneous measurement of two golden channels:</u>

1) **testing Spin-Statistics connection searching for PEP violating atomic transitions.**
2) **Testing the characteristic spontaneous radiation (Z dependent) in the range (1-15 keV).**

<u>We will enhance sensitivity toward the Planck scale, with the potential to reveal the first signal of a unified theory.</u>

Minimal references

complete review of phenomenological collapse models, but not updated for the experimental part:

Rev. Mod. Phys. 85, 471-527 (2013)

arXiv:1204.4325 [quant-ph]

updated review on experimental tests of collapse models:

Nature Physics 18, 243-250 (2022)

arXiv:2203.04231 [quant-ph]

review of gravitational decoherence theories:
AVS Quantum Sci. 4, 015602 (2022)
arXiv:2111.02462 [gr-qc]

Thank you !