New Limits on Spontaneous Wave Function Collapse Models with the XENONnT Data

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We have analyzed recently published XENONnT data for the spontaneous X-ray emission signature predicted by the objective wave function collapse model of quantum mechanics. With extremely low background and large exposure, XENONnT data can be used to completely exclude the theoretically predicted collapse parameters of continuous spontaneous localization (CSL) model suggested by Ghirardi, Rimini and Weber. Our result strongly suggests that the simplest version of the CSL model with the white-noise assumption is unlikely to provide answers to the long-standing measurement problem of quantum mechanics and motivates pursuits of more complex versions of the theory. If the result is interpreted with the Diósi-Penrose gravitational wave function collapse model, our limit improves the previous limit by a factor of 5.7. Detailed analysis using more precise background modelling can further improve the limits.

While quantum mechanics is extremely successful in predicting experimental results, the cause of wave function collapse, which is generally accepted in the standard formulation of quantum mechanics, is not known. Moreover, while quantum mechanical theory in principle does not make a distinction between microscopic and macroscopic objects, observations suggest that the superposition of two different states can be maintained more easily in microscopic systems than in the macroscopic world [1–3]. The questions of why, how and at what scale this transition between the probabilistic and deterministic evolution during quantum mechanical measurements occurs are yet left open.

The quantum-to-classical transition can be explained if one postulates a mechanism where the collapse is induced by a specific property of the system closely related to the number of constituents of that system. Various theoretical and experimental studies have been conducted in this direction in an effort to provide some answers to this long-standing measurement problem of quantum mechanics [4, 5]. The spontaneous wave function collapse models, also known as the objective collapse theories, are a collection of proposed solutions to describe how the classical world emerges from the framework of quantum mechanics [4–12]. In these models, the standard unitary form of the Schrödinger equation is only an approximation of the real dynamics. The theories extend the Schrödinger equation by adding non-linear and stochastic terms that perturb the dynamics of the system. For small isolated systems, the new terms are negligible and the probabilistic evolution is recovered. However, since the perturbation scales with the size of the system, larger systems have the total wave function that is well-localized in space. The small deviation from the unitary Schrödinger equation is predicted to leave a detectable signature in the system, making these theories experimentally testable.

One of the most studied objective collapse theories is the continuous spontaneous radiation (CSL) model. The CSL model postulates the existence of a stochastic noise field that induces the spontaneous collapse of the wave function [6–9, 13–15]. Particles undergo spontaneous localization at specific positions following the Poissonian distribution of the noise field, which is characterized by a mean frequency \( \lambda \) and a correlation length \( r_C \) that define the spatial resolution of the collapse. Another well-studied model is the Diósi-Penrose (DP) model, where the gravitational distortion of spacetime is thought to cause the spontaneous localization [11, 12, 16]. Both the CSL and the DP models predict a small change in the energy of particles when the localization occurs, which accelerates the particles. If this acceleration occurs for charged particles such as electrons, it can induce a \( 1/E \)-like bremsstrahlung X-ray signature that is not predicted by conventional quantum mechanics [14–22].

In this article, we set a new limit on these spontaneous wave function collapse models using recently released electron recoil data [23] from XENONnT dark matter search [24–26]. This experiment uses 8.5 tonnes of ultrapure liquid Xe and extensive background control to search for Xe nuclear recoils from the scattering of dark matter particles. The background level in the 1–30 keV range is as low as \((16.1\pm1.3)\text{ counts/(t-yr-keV)}\), and the reported exposure is 1.16 t-yr. The total event selection efficiency is \(\approx 80\%\) above 12 keV. We demonstrate that, with its extremely low background level and large exposure, XENONnT can set the most stringent upper limit on the rate of the X-ray signatures predicted from the spontaneous collapse models.

The rates of X-rays predicted in the CSL model under two different assumptions on the characteristics of the collapse are summarized in Ref. [17]. If the coupling of the particle to the stochastic noise field is assumed to be independent of the particle mass \( m_X \) (non-mass-proportional version, n-m-p), then the resulting acceleration of the charged particle is inversely proportional to \( m_X \). In this case, the radiation signature in a detector material is dominated by the electron contribution due to the higher nuclear recoil energy. The rate of X-rays predicted in the CSL model is therefore inverse proportional to \( m_X \). However, if the coupling to the noise field is proportional to the particle mass \( m_X \) (mass-proportional version, m-p), then the rates of X-rays are independent of the particle mass.

The XENONnT data can be used to completely exclude the theoretically predicted collapse parameters of the CSL model with the white-noise assumption [17]. This result strongly suggests that the simplest version of the CSL model is unlikely to provide answers to the long-standing measurement problem of quantum mechanics and motivates pursuits of more complex versions of the theory. If the result is interpreted with the Diósi-Penrose gravitational wave function collapse model, our limit improves the previous limit by a factor of 5.7. Detailed analysis using more precise background modelling can further improve the limits.
to the large mass difference between the quasi-free electron and the nucleus. The $1/E$-dependent X-ray emission rate $d\Gamma(E)$ from the charged particle acceleration is then given by

$$\frac{d\Gamma(E)}{dE} = A_f \times \frac{\hbar \lambda}{4\pi^2 \epsilon_0 m_e^2 c^3 r_C^2 E} \equiv \frac{R_0}{E},$$ (1)

where $A_f$ is a charge-dependent amplification factor, $\epsilon_0$ is the vacuum permittivity, $c$ is the speed of light in vacuum, and $m_X = m_e$ is the electron rest mass [17]. Electrons in Xe atoms can be considered quasi-free if their binding energy is more than 10 times smaller than the energy of the emitted photons [20]. If we consider X-rays with energy above 12 keV, the 44 outermost electrons above 3s shell (binding energy of 1.15 keV) can be considered quasi-free. The amplification factor becomes $A_f = N_{Xe} N_e e^2$ where $N_{Xe}$ is the number of $^{136}$Xe atoms per unit mass, $N_e = 44$ is the number of quasi-free electrons in Xe, and $e$ is the elementary charge [17].

If the coupling to the noise field is proportional to $m_X$ (mass-proportional version, m-p), then the power injected from the noise field to the particle is proportional to $m_X^2$, and hence the acceleration becomes independent of $m_X$. In this case, $m_X$ in Eq. 1 is replaced by the nucleon mass $m_0$ [17]. The limit on $\lambda/r_C^2$ is suppressed by a factor of $m_0^2/m_e^2 \approx 3.0 \times 10^{-7}$ due to the difference between $m_0$ and $m_e$. In this case, the Xe nucleus can have a non-negligible contribution to the X-ray signature as its contribution is not suppressed by the particle mass. In particular, in the range where the emitted photon’s wavelength is small enough to distinguish the nucleus from the electron orbit ($\lambda < 0.1$ nm) but not too small to distinguish individual nucleons ($\lambda > 10^{-5}$ nm), the nucleus can be considered as a single charged particle [21]. This corresponds to the energy range of $10^{-10}$ keV. The amplification factor $A_f$ then becomes $A_f = N_{Xe}(Z^2 + N_e)e^2$. The $Z^2$ term accounts for the coherent emission from the nucleus, and the $N_e$ term is contribution from the electrons. We choose the region of interest (ROI) for our search to be above 12 keV to explore both cases.

Figure 1 shows the XENONnT electron recoil data from Ref. [23]. The efficiency is illustrated as a solid blue line. Two distinctive background peaks appear in the (27–90) keV region. For simplicity of the background modelling, we excluded this region from our ROI. Hence, our ROI consists of two discontinuous energy regions, (12–27) keV and (90–140) keV.

The dominant background sources in this region are identified as the $^{214}$Pb $\beta$-decay, which can be estimated as a flat background within the ROI, and the two-neutrino double beta decay of $^{136}$Xe with the $Q$-value of 2457.83 keV, which can be approximated as a linear background. The simplest spectral model $\mathcal{P}(E)$ as a function of energy $E$ in the ROI can be written as

$$\mathcal{P}(E) = \epsilon(E) \times \left[\frac{R_0}{E} + (AE + B_1) + B_2 \Theta(E - 90)\right],$$ (2)

where $\epsilon(E)$ is the efficiency, $R_0$ is the intensity of the X-ray signature from the CSL model, $(AE + B_1)$ is the linear plus flat contribution from the backgrounds, and $B_2 \Theta(E - 90)$ term represents a possible difference in the flat components between the lower and the higher region. In particular, a possible contribution from $^{133}$Xe above $\approx 80$ keV is mentioned in Ref. [23]. $B_1$ is set to vary freely in the fitting process, while $A$ and $B_1$ are constrained to be $\geq 0$. $R_0$ was initially unconstrained to observe the significance of the fit, and then constrained to be $\geq 0$.

We applied MINOS optimization algorithm [27] to fit Eq. 2 to the data in Fig. 1. When $R_0$ is unconstrained, we find the best-fit value of $R_0 = -51 \pm 70$ counts/(t-yr), which is consistent with a null observation. By constraining $R_0$ to be $\geq 0$, we set an upper limit of $R_0 = 96.0$ counts/(t-yr) at 95% confidence level (CL). The 95% CL fit in the ROI is illustrated in Fig. 2. With Eq. 1, we obtain a 95% CL lower bound on the non-mass-proportional CSL parameters at $\lambda/r_C^2 = 4.4 \times 10^{-8}$ s$^{-1}$m$^{-2}$ (Fig. 3, red dotted line), which is a factor of 118 more stringent than the previous limit [23]. For the m-p version of the CSL model, Eq. 1 yields $\lambda/r_C^2 = 2.2 \times 10^{-3}$

**FIG. 1.** The XENONnT electron recoil data, taken from Ref. [23]. The total efficiency is shown in blue line. The ROI of (12–27) keV and (90–140) keV are set to satisfy the X-ray emission conditions described in the text, while avoiding the background peaks.

**FIG. 2.** The 95% CL fit in the ROI of (12–27) keV and (90–140) keV for the X-ray radiation signature predicted from the CSL model. The 95% CL upper limit value for $R_0$ is 96.0 counts/(t-yr).
FIG. 3. Upper limits on two different versions of the CSL using the XENONnT data [23]. The upper limit for the non-mass-proportional version is shown as a red dotted line, and the limit for the mass-proportional version is shown as a solid line. The newly excluded parameter space is shown as a shaded region. Other limits from previous works are also shown for comparison, which include cold atom experiments (brown) [28, 29], gravity wave experiments (olive) [30], mechanical cantilever experiments (purple) [31–33], and measurements of dark bulk heating rate on crystal at low temperature (blue) [34, 35]. The limits from previous X-ray study [22] are shown in green lines. The black solid line and the gray shaded region mark the theoretical lower limit [36]. Theoretical predictions based on different assumptions are shown as black error bars (Adler, [14]), a gray error bar (Bassi, [37]), and a black hollow circle (GRW, [6]).

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\frac{d\Gamma(E)}{dE} = \frac{2 e^2 G Z^2 N_{Xe}}{3 \pi^3/2 \epsilon_0 c^3} \frac{1}{R_{DP}^2} \frac{1}{E} \equiv \frac{R_0}{E},
\]

where the \(G\) is the gravitational constant and \(R_{DP}\) is the characteristic cut-off length of the DP model [16]. With the same upper limit on \(R_0\), we get a 95% CL lower bound on the cut-off length of \(R_{DP} > 2.8 \times 10^{-9}\) m. This is a factor of 5.7 improvement over the previous best limit of \(4.94 \times 10^{-10}\) m [22].

We have analyzed recently released XENONnT electron recoil data in the [12, 27] keV and [90, 140] keV region to search for the X-ray signature predicted from the spontaneous wave function collapse models. For both non-mass-proportional and mass-proportional versions of the CSL model, we improved the previous limits on the CSL parameters \(\lambda/r_R^3\) by more than two orders of magnitudes. In particular, our limits are the first to exclude the theoretical prediction by Ghirardi, Rimini and Weber [6] for the m-p CSL model. Our limits strongly disfavor the simplest versions of the CSL model with the white-noise assumption, and experimentally motivate searches for more complex versions of the CSL. We also set the most stringent lower limit to date on the Diósi-Penrose gravitational wave function collapse model, adding significance to the previous results.

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