Detecting continuous spontaneous localization with charged bodies in a Paul trap

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Continuous spontaneous localization (CSL) is a model that captures the effects of a class of extensions to quantum theory which are expected to result from quantum gravity and is such that wave-function collapse is a physical process. The rate of such a process could be very much lower than the upper bounds set by searches to date and yet still modify greatly the interpretation of quantum mechanics and solve the quantum measurement problem. Consequently experiments are sought to explore this. We describe an experiment that has the potential to extend sensitivity to CSL by many orders of magnitude. The method is to detect heating of the motion of charged macroscopic objects confined in a Paul trap. We discuss the detection and the chief noise sources. We find that CSL with standard parameters could be observed using a vibration-isolated ion trap of size 1 cm at ultralow pressure with optical interferometric detection.

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Since quantum technologies have developed rapidly in recent years, it is becoming possible to test quantum theory on macroscopic objects. One of the interesting questions that arises is that of wave-function collapse. Although superposition states of microscopic objects have been observed in many experiments, and such tests have been extended to mesoscopic systems, such as large molecules [1], observations on macroscopic objects have, to date, been ambiguous since the lack of observable interference could be attributed either to a fundamental collapse effect or to a lack of experimental precision. However, the possibility of a true collapse process in nature is attractive because such a process is expected to arise naturally in models of some sort of quantized nature of space-time [2] and because it would provide a solution to the quantum measurement problem. The latter is the problem famously illustrated by Schrödinger's cat, namely, that it is hard to reconcile our everyday experience with the implications of quantum theory as currently understood.

One of the theoretical efforts to account for wave-function collapse is the continuous spontaneous localization (CSL) model [3–9]. In this model wave-function collapse occurs spontaneously, and the collapse strength is proportional to mass. It thus predicts that long-lived spatial superposition states of massive objects would not be found in nature.

Potential phenomena due to CSL include the decoherence of a superposition state [10–14], linewidth broadening [15], heating of a mechanical oscillator [16–21], and diffusion in free space [8,22,23]. All these can also be caused by ordinary decoherence associated with uncontrolled interactions with the environment, therefore low noise is the crucial consideration in the design of any experiment in this area. In this paper we investigate the potential of a Paul trap (often called an "ion trap") to provide the low-noise environment that is required. We develop an idea of Collett and Pearle's [8] in which one seeks to detect the heating due to CSL of a charged macroscopic object confined in such a trap [8,24,25]. We evaluate the noise sources and detection possibilities sufficiently well to demonstrate the feasibility of the method. We show that CSL with the parameters suggested by Ghiradi, Rimini, and Weber (GRW) [3] could be detected in a trap of size of ~ 1 cm at a pressure of 10^{-13} Pa in a time on the order of 1 min. This exceeds by several orders of magnitude the sensitivity expected from detection methods proposed to date.

CSL is characterized by two parameters: the collapse rate of a nucleon λ and the critical length scale r_c [8]. An equivalent set of parameters $\gamma = (4\pi r_c^2)^{3/2}\lambda$ and $\alpha = r_c^{-2}$ may also be used [9]. A standard choice is $\lambda \sim 10^{-16}$ s^{-1} and $r_c \sim 10^{-7}$ m; we will refer to these as "GRW values" [3]. The range of values not yet excluded by observations extends very much higher than this [cf. Fig. 2(b)] [9,21] so that even to approach a sensitivity sufficient to detect GRW values would be a significant achievement.

One effect due to CSL of a rigid body is to raise the energy in the center-of-mass motional (CMM) degrees of freedom. The energy raising rate (ERR) (roughly speaking, the heating rate) can be written in the form

$$\Upsilon = \chi\hbar^2\lambda r_c \rho u^{-2}, \tag{1}$$

where ρ is the density of the material, u is the mass of a nucleon, and the dimensionless factor χ depends on the shape of the rigid body and the external potential. For a sphere of radius L in free space, $\chi = 2\pi I/x$ for each of the three motional directions, where $x \equiv L/r_c$, and [8]

$$I = 1 - 2x^{-2} + (1 + 2x^{-2})\exp(-x^2). \tag{2}$$

The maximum value is $\chi \simeq 1.7202$ at $L \simeq 2.38 r_c$ [see Fig. 1(a)]. For a cube of side $2L$ in a one-dimensional (1D) harmonic trap, $\chi = I_{12} I_3/x^3$ [16–18], where $I_3 = 2[1 - \exp(-x^2)]$ and

$$I_{12} = [\exp(-x^2) - 1 + \sqrt{\pi}x\,\mathrm{erf}(x)]^2. \tag{3}$$

Here, $\mathrm{erf}(x) \equiv 2\pi^{-1/2}\int_0^x \exp(-t^2)dt$ is the error function. For the cube, χ is maximized at $L \simeq 1.92 r_c$ with the value $\chi \simeq 1.5943$.

Taking GRW parameter values and $\rho = 22\,587$ kg/m^3 (the density of osmium), the maximum ERR for a sphere in free space is $\Upsilon \simeq 1.57 \times 10^{-33}$ J/s or 6.8 nK/min, and for a cube it is a little lower. The essence of the proposed experiment is to trap and cool an object of this size and then determine whether

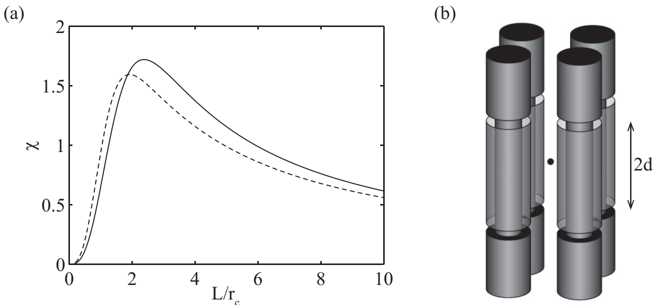

FIG. 1. Energy raising rate and Paul trap. (a) CSL factor χ of a sphere of radius L in free space (full line) and a cube of side $2L$ in a 1D harmonic potential (dashed line). (b) Example electrode structure for a Paul trap.

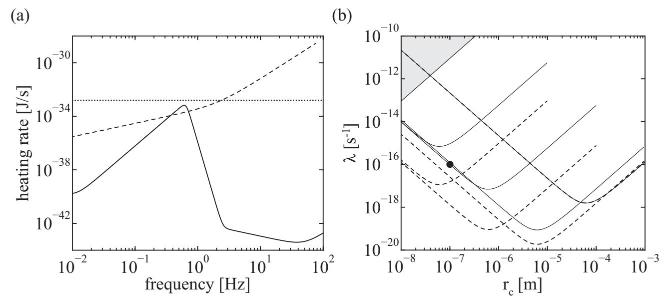

FIG. 2. Heating rate and detection limit. (a) Heating rate owing to various processes, calculated for a singly charged osmium sphere of radius 0.238 μm, mass of 7.7×10^{11} a.u.. Full curve: Γ_x (mechanical), dashed curve: Γ_E (electric field), dotted line: CSL heating Υ at GRW parameters. (b) Smallest detectable value of λ as a function of r_c for four sizes of a trapped osmium sphere: $L = 0.1,1,10,100$ μm. The minimum of the corresponding curve is in the vicinity of L. The continuous curves are for background pressure $p = 10^{-12}$ Pa, the dashed curves are for $p = 10^{-14}$ Pa. Two curves for $L = 100$ μm are overlapped. The shaded region is the currently excluded region, set by spontaneous x-ray emission [38]. The dot indicates GRW values.

its CMM temperature in 1D has increased by 10 nK after 90 s (or 100 nK after 15 min) [26].

There are two main experimental issues. First, can one construct an apparatus in which the heating caused by other noise sources does not dominate that due to CSL? Second, can one detect a heating rate of this order in a reasonably short amount of time?

The main contributions to heating are from mechanical vibrations, electric-field noise, magnetic-field noise, and background gas collisions. Electric dipole radiation from the oscillating charged rigid body is negligible as is the momentum diffusion caused by scattering blackbody radiation at 70 K [27].

Suppose a change δR in a stochastic variable R causes the force on the trapped body to vary by δF. Then the fluctuations of R cause an average heating rate given by

$$\Gamma_R = \frac{1}{4m}\left(\frac{\partial F}{\partial R}\right)^2 S_R(\omega_0), \tag{4}$$

where m is the mass of the trapped body, ω_0 is the angular frequency of its simple harmonic motion, and S_R is the one-sided power spectrum of the noise in R.

First consider mechanical noise in which trap electrodes are displaced by a distance x, for example, owing to seismic noise and thermal vibrations of the electrode surfaces. Then $\partial F/\partial x = m\omega_0^2$, so the heating rate owing to these fluctuations is $\Gamma_x = m\omega_0^4 S_x/4$, where S_x is the positional noise. Trap electrodes (to be discussed) will have dimensions in the range of millimeters to meters, and we require stability of the apparatus relative to a local inertial frame (that is, the apparatus should maintain, as far as possible, a fixed acceleration relative to a frame falling freely in the local gravitational field). There are two main techniques to achieve high stability: active methods based on laser interferometry and passive methods based on mechanical filters, which are low-frequency resonators (e.g., pendulums or masses on springs). Above its resonance frequency f_0 the transmission of each filter is proportional to $(f_0/f)^2$, and by cascading filters one obtains higher powers. It will emerge that the frequency scale we are interested in here is in the vicinity of that used in gravitational wave sensors, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo, and these illustrate the state of the art. In an ordinary optics laboratory, optical tables can be stabilized to a level of 10^{-10} m$/\sqrt{\text{Hz}}$ between 10 mHz and 100 Hz [28] or somewhat better. The advanced LIGO positioning platform is designed to achieve 10^{-11} m$/\sqrt{\text{Hz}}$ at 1 Hz by active stabilization [29]. The mechanical filters then achieve lower noise at higher frequencies. For the purpose of this paper we will assume the noise is about an order of magnitude larger than that measured at the LIGO interferometers [30] and is given by the following model, which reproduces the design study for the Virgo experiment described in Ref. [31],

$$S_x = a_1^2 f^{-5} + a_2^2\left(f_0^{20} + f^{20}\right)^{-1} + a_3^2 f^{-1}, \tag{5}$$

where $f_0 = 0.65$ Hz and if f is in hertz and S_x is in units of m^2/Hz then the coefficients are given by $a_i = \{1.5,1500,0.0006\} \times 10^{-15}$. The three terms model the effects of thermal vibrations in the pendulum suspensions, seismic vibrations after filtering, and thermal vibrations of the electrode surfaces, respectively. Below f_0 this gives $S_x \simeq 10^{-20}$ m^2/Hz, achieved by active stabilization. The resulting heating rate for an example mass in a harmonic trap is shown as a function of frequency by the full line in Fig. 2(a).

The conclusion so far is that mechanical noise can be suppressed sufficiently for it to produce a heating rate small compared to the CSL effect (Υ) at the GRW parameter values, and we have a described a model which allows us to explore a range of parameter values.

Next, consider electric-field noise. The force owing to an electric-field fluctuation δE is $q\,\delta E$ where q is the charge of the trapped object, so the heating rate is $\Gamma_E = (q^2/4m)S_E(\omega_0)$. This neglects cross coupling between noise fields and the rf trapping fields, which is acceptable since the latter makes a small correction and we only need an approximate estimate. The electric-field noise in a Paul trap is notoriously difficult to calculate from models of the materials and electronic sources which drive the trap, but it can be estimated with reasonable confidence by using existing data from a number of experiments. Typically one measures the heating rate of a trapped ion and infers S_E. This has been performed for a large number of traps with sizes between a fraction of a millimeter and a centimeter in experiments designed for low noise. The vibrational frequency of the trapped ion is typically in the range of 10^5–10^6 Hz in such experiments, so they do not explore the low-frequency noise which we are interested in. The observations are consistent with a noise S_E scaling as ω^{-n} with $0 < n < 1$ for the rather restricted range of frequencies typically studied in any given trap. We will assume the scaling is given by $n = 1$ and adopt the following model:

$$S_E = \left[\left(b_1 + b_2 V_Q^2\right)d^{-2} + b_3 d^{-4}\right]\omega^{-1}, \tag{6}$$

where b_i are coefficients, V_Q is the applied voltage that produces the constant quadrupole field, and d is the distance from one of the electrode surfaces to the center of the trap [Fig. 1(b)]. The terms b_1 and b_2 allow for contributions to the noise both unrelated to V_Q and increasing with V_Q. The terms in d^{-2} describe noise owing to the fluctuation of the voltage on the whole surface of any one electrode, and the term in d^{-4} describes noise owing to voltage fluctuations in a collection of independently fluctuating patches where each patch has a size small compared to the distance to the point where the field is measured.

The value of the coefficient b_3 is strongly dependent on the temperature of the electrode surfaces [32], and one would expect some temperature dependence in b_1. In the present paper we will assume the electrodes are at room temperature, and we will typically be interested in large traps where the b_3 term is negligible (although we include it anyway). The data reported in Ref. [33] are approximately reproduced by the parameter values $b_1 = 1.7 \times 10^{-14}$ V^2, $b_2 = 1.1 \times 10^{-17}$, and $b_3 = 2.6 \times 10^{-19}$ V^2 m^2. To arrive at these values, we estimated the relative contributions of the b_1 and b_2 terms; these will vary from case to case, but our deductions give a sufficient estimate of Γ_E to determine whether the proposed experiment is feasible.

In thus using the data from existing experiments, we will be making a large extrapolation in frequency (from 10^5 to 0.1 Hz), but since we assume $1/f$ noise, this is a conservative estimate. The model predicts that the field noise below 1 Hz is similar to that which would be given by voltage noise on the order of some tens of nanovolts for applied voltages on the order of tens of volts; this is a reasonable value since we are only concerned with the noise component remaining after common mode rejection, and each pair of end cap electrodes can be made of a single lump of metal [34]. The rms electric field we thus obtain is similar to the electric field that would be produced at the trap center by a single electron on an electrode surface.

The dashed curve in Fig. 2(a) shows the heating rate owing to electric-field noise for an example case. Here we specify values of d in the range of 0.1 mm to 1 m and adopt $V_Q = 20$ V. We then calculate the vibrational frequency ω_0, which scales as $1/d$, and obtain $S_E(\omega_0)$ from Eq. (6). The result of the scaling with d is that lower frequencies correspond to larger traps and consequently less noise. We thus deduce that, for vibrational frequencies below about 1 Hz, which here corresponds to a trap of size $d \simeq 1$ cm, the electric-field noise produces less heating than CSL.

Magnetic-field noise can heat the CMM by coupling to the current associated with the oscillating charge or to the magnetic dipole moment μ of the rigid body itself. The former contribution is negligible; the latter affects neutral or charged bodies equally, whose effect is also negligible for $\mu \ll 10^7$ Bohr magnetons for the typical length scale of the field fluctuation of $d = 1$ cm [35]. Expected values of μ are comfortably in this region.

If the trapped body is conducting, the ac field of the Paul trap creates currents in it, and these can couple to magnetic-field noise. The induced electric dipole between one part of the sphere and another is on the order of $d_0 \simeq \epsilon_0 L^3 E$ where $E \simeq Q_{\rm ac} L$ is the electric field at the sphere's surface owing to the trap quadrupole $Q_{\rm ac} \simeq V_{\rm ac}/d^2$. The magnetic force on the induced currents is approximately $\Omega_{\rm ac} d_0 B$ where $\Omega_{\rm ac}$ is the Paul trap drive frequency. In the absence of asymmetry, these forces are on different parts of the sphere balance, but even if this were not so, the resulting heating rate would be on the order of $(\Omega_{\rm ac} d_0)^2 S_{\rm B}/4m \approx 10^{-65}$ J/s, which is negligible.

Next we consider the effect of collisions with background molecules in the vacuum chamber. The effect depends on whether individual collisions can be detected. If they cannot, then they provide diffusive heating at the rate of $\Gamma_c = (m_{\rm g}/m) p\sigma\bar{v}$, where $m_{\rm g}$ is the mass of a background atom or molecule, p is the pressure, and $\sigma = 2\pi L^2$ is the collision cross section for heating in 1D of a sphere of radius L. We thus find an upper bound on p in order that collisional heating should be smaller than Υ,

$$p < \Upsilon m/(2\pi L^2 \bar{v} m_{\rm g}). \tag{7}$$

At the low pressure required, cryogenic pumping is needed, and therefore the residual gas is mostly light gases, such as hydrogen and helium. Taking helium at room temperature and GRW parameters, we find $p < 7 \times 10^{-13}$ Pa. This is challenging but possible (the lowest reported pressure is around 7×10^{-15} Pa [36]).

At a pressure of 10^{-13} Pa, the collision rate is on the order of $1/90$ s^{-1}.

So far we have shown that the expected noise sources do not dominate CSL in the significant parameter regime. It remains to explore whether or not the CSL effect is itself measurable. That is, is it feasible to detect some tens to hundreds of nanokelvins of heating of the motion of the trapped rigid body? One can readily suggest experimental methods to show that it is. One may detect the position of the body in 1D by reflecting a laser beam off it and using an interferometric method. By repeating the measurement after a quarter cycle of the oscillation in the trap, one locates the body in phase space. A natural limit of such methods is the "standard quantum limit" [37]. By studying phase estimation from scattered light pulses, one finds that in principle the 1D position and momentum of a measured object can be determined to within an area on the order of $\hbar$ in phase space. Such a precision, when combined with feedback to the trap electrodes, amounts to the ability to prepare the object near to its ground state of motion, which is in practice very difficult to achieve for macroscopic objects. However we do not need to assume that precision here. Suppose that in any given run of the experiment one achieves measurement precisions Δx and $\Delta p = m\omega_0 \Delta x$ such that $\Delta x\, \Delta p = 2\bar{n}\hbar$ for some $\bar{n} \gg 1$.

Then the initial state of the sphere can be prepared with energy $E_0 = (1/2)m\omega_0^2\Delta x^2 = (1/2)\omega_0\Delta p\,\Delta x = \bar{n}\hbar\omega_0$, and one can detect energy increases of this order. At $\bar{n} = 500$, for example, $E_0/k_B = 2.4$ nK when $\omega_0/2\pi = 0.1$ Hz. CSL will give this amount of heating in 23 s.

Our cooling method consists of a detection followed by an adjustment of the trap potential. This is like the "stochastic cooling" widely adopted in particle storage rings but here applied to a single particle. We propose optical detection and electrical feedback (to the trapping field) to provide the momentum kick. The cooling limit is set by the precision of these two steps and has been indicated conservatively above. The problems of preparing suitable spheres and loading them into a Paul trap have largely been solved [24].

So far we have surveyed the potential to detect CSL at the parameters suggested by GRW. In practice one would test rigid bodies of a number of different sizes in order to explore different regions of parameter space. One would also accumulate data over long runs. Our paper has shown that even a single run of duration on the order of 1 min could detect CSL at the GRW parameters. A data set accumulated over longer periods would provide the means to check for systematic errors and reduce the statistical uncertainty.

By using the noise models discussed, we can map the region of parameter space in which CSL could be detected by this approach, see Fig. 2(b). The boundaries indicated are only approximate, but they suffice to show that this is a feasible experimental technique, which could set an upper bound on λ many orders of magnitude below the currently known upper bound, or indeed discover CSL. The concept of the method is due to others [8]; the contribution of the present paper is to discover suitable parameters for the apparatus and to show that the concept is sound. The results shown in Fig. 2(b) are mostly limited by collisions and therefore are not very sensitive to the trap electrode size and voltage. A size of $d \sim 1$–10 cm is suitable for $L < 10\ \mu$m; for larger spheres a smaller trap is useful in order to keep the vibrational frequency above 0.01 Hz (below this we would hesitate to trust our noise models).

We have discussed effects which increase the kinetic energy of the collapsing object. An apparatus based on the same Paul trap would be a good starting point for more sophisticated experiments designed to detect motional decoherence. Superpositions of motional states could be produced by adapting various techniques that have been applied to single trapped ions [39]. For example, one could use a diamond sphere with a nitrogen-vacancy center or a semiconducting sphere containing a quantum dot and obtain a spin-dependent dipole force from the interaction with an optical standing wave. More generally, one would seek a controlled coupling between the center of mass of the trapped microsphere and some other entity or degree of freedom which can be prepared in a superposition. The CSL family of phenomenological theories offers the potential to solve what many recognize as the measurement problem, not so much by a modification to quantum mechanics, as a way of capturing what might naturally arise in various possible frameworks of quantum theories with dynamic space-time [40].

The central claim of this paper is that the Paul trap, operated in the parameter regime we have described and with optical detection, offers a sensitivity to heating from CSL that exceeds by many orders of magnitude that which has been predicted for existing proposals. This remains a theoretical study not an achieved experiment, so it has to be assessed in terms of the correctness of the analysis. The system we have studied is simple, and the assumptions we have made are conservative. The technical challenge lies mainly in the combination of vibration isolation and ultralow pressure. Our evaluation would be applicable to testing other quantum models that can be detected by an energy raising rate [41].

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