scientific reports

OPEN

Examples of atoms absorbing photon via Schrödinger equation and vacuum fluctuations

Yongjun Zhang

The absorption of photons by atoms encompasses fundamental quantum mechanical aspects, particularly the emergence of randomness to account for the inherent unpredictability in absorption outcomes. We demonstrate that vacuum fluctuations can be the origin of this randomness. An illustrative example of this is the absorption of a single photon by two symmetrically arranged atoms. In the absence of a mechanism to introduce randomness, the Schrödinger equation alone can govern the time evolution of the process initially. Then, it becomes stuck, and an entangled state of the two atoms emerges. This entangled state consists of two components: in one, the first atom is excited by the photon while the second is in the ground state, and in the other, the second atom is excited while the first remains in the ground state. These components form a superposition state characterized by an unbreakable symmetry in the absence of external influences. Consequently, the absorption process remains incomplete. When vacuum fluctuations come into play, they can induce fluctuations in the weights of these components, akin to Brownian motion. Over time, one component diminishes, thereby breaking the entanglement between the two atoms and allowing the photon absorption process to conclude. The remaining component shows which atom completes the photon absorption. Vacuum fluctuations not only introduce randomness but also have the potential to give rise to the Born rule in this context. Furthermore, the Casimir effect, which is closely tied to vacuum fluctuations, presents a promising experimental avenue for validating this mechanism. Similar studies can also be conducted with varying numbers of atoms.

Quantum optics probes the intricate interactions between light and matter, surpassing the realm of classical optics to examine the behavior of individual photons and their interactions with atoms and subatomic particles[1]. A fundamental aspect in this domain is the absorption of photons by atoms, a core quantum-mechanical process characterized by an atom transitioning from a lower to a higher energy state, the excited state, upon photon absorption. Studying this process offers crucial insights into quantum mechanics, particularly in unraveling four interconnected perspectives that remain less understood.

First, there is a challenge in aligning quantum unitary time evolution[2] with the discrete eigenstates of atoms. Consider a hydrogen atom transitioning from its ground state to an excited state due to photon absorption. In a scenario without discrete states, unitary time evolution could seamlessly map the initial state to the final state. However, the inherent discreteness of atomic eigenstates complicates this mapping. According to measure theory[3], such a direct mapping would effectively have a measure of zero, thereby making the transition impossible. To enable the transition, the rigid framework of unitary time evolution must be relaxed. This relaxation should allow multiple initial states to converge to the same final state, inherently leading to some loss of information from the initial state and the subsequent emergence of randomness.

Second, the nature of randomness in quantum mechanics remains enigmatic. Einstein's famous dictum, "God does not play dice," challenges the notion of intrinsic randomness and resonates through various interpretations of quantum phenomena. The Copenhagen Interpretation[4,5] attributes randomness to wave function collapse according to the Born rule[6]. However, this interpretation has been contested due to its implications of observer-dependency and perceived incompleteness of reality[7–9]. Alternative approaches include the deterministic pilot wave theory, which posits hidden variables and a guiding wave[10–12], and the many-worlds interpretation[13,14], which suggests a branching universe for each quantum event, rendering randomness as emergent. Decoherence theory, on the other hand, deals with randomness at the statistical level of quantum ensembles[15–20]. The Ghirardi-Rimini-Weber (GRW) model[21–24] and its successor, the Continuous Spontaneous Localization (CSL)

Science College, Liaoning Technical University, Fuxin 123000, China. email: yong.j.zhang@gmail.com

model[25–28], introduce spontaneous collapse into the quantum framework to account for state vector reduction, but the source of underlying randomness remains unspecified.

Third, research on ensembles may not fully elucidate the dynamics of individual quantum systems, underscoring the need for distinct approaches at these two analytical levels. An ensemble-based approach is often indispensable and more feasible, particularly when detailed knowledge of the underlying dynamics is sparse. A prime example is Einstein's investigation of Einstein coefficients[29] through thermodynamic considerations, a domain intrinsically tied to the concept of ensembles. However, it is crucial to recognize that ensemble studies are not a replacement for delving into the intricacies of individual quantum systems. This becomes especially apparent in the context of the Born rule: while its application in ensemble scenarios is often direct and taken for granted, in the case of single systems, the rule's relevance is dictated by the dynamics of the system itself, which determine all potential outcomes and their probabilities, and the Born rule must naturally arise from the dynamics. Some elements of the dynamics involve randomness. These elements might be overlooked in ensemble-focused theories, but are essential in the analysis of individual systems. In the context of the CSL model, Pearle's use of the gambler's ruin problem as an analogy has facilitated the derivation of the Born rule for individual quantum systems[30,31].

Finally, determining the exact nature of photon absorption-whether it is continuous, instantaneous, or a hybrid process starting continuously and completing instantaneously-remains an open question. Bohr's model[32] depicts electron transitions in hydrogen atoms as instantaneous, a view echoed by the Copenhagen interpretation, especially in the context of treating photon absorption as a quantum measurement. This perspective aligns well with the randomness introduced by the Born rule. On the other hand, the CSL model proposes a continuous process for introducing randomness[25,26], yet it contends with the 'tail problem,' where remnants of the wave function persist post-collapse[31]. Furthermore, the derivation of Einstein coefficients within quantum mechanics implies a continuous process[33]. Extending this concept to quantum electrodynamics[34] suggests that vacuum fluctuations play a role in atom-photon interactions and may trigger spontaneous emission[35,36]. These fluctuations, arising from Heisenberg's uncertainty principle[5], occur because a quantum field's amplitude and rate of change cannot simultaneously be zero, even in a vacuum. The Casimir effect provides empirical evidence for these vacuum fluctuations[37,38].

This paper investigates the absorption of a single photon by atoms, based on two hypotheses: the absorption process is continuous, and its inherent randomness arises from vacuum fluctuations. Our focus is primarily on individual systems, as opposed to ensembles. We begin by studying an example of two atoms absorbing a single photon. Next, we examine the role of vacuum fluctuations and draw an analogy with Brownian motion. Following this, we propose methods to validate the mechanism experimentally. Subsequently, we analyze two additional examples before discussing the interplay of information and randomness.

Two atoms absorbing one photon

We consider a scenario depicted in Fig. 1, where a single photon interacts with two identical atoms that are initially in their ground states. For simplicity, we assume that each atom has only two energy levels: the ground state and an excited state, with an energy difference of ΔE. If the frequency ν of the photon is off-resonance—i.e., $h\nu \neq \Delta E$, where h is Planck's constant—the atoms will not absorb the photon. Instead, the photon will be diffracted, leading to an interference pattern. In an extended atomic lattice, this pattern would correspond to Bragg's law[39].

The system is initially symmetric, with the photon's wave function interacting equally with both atoms. However, this symmetry is broken upon photon absorption, as one atom becomes excited while the other remains in the ground state. This symmetry breaking introduces randomness.

An instantaneous process would imply infinite changes in energy and momentum, which are physically unrealistic. Therefore, at least in the initial stages of absorption, the process is continuous. This process is governed by the Schrödinger equation:

$$i\,\hbar\frac{d}{dt}|\Psi_\mathrm{I}\rangle = H_\mathrm{I}|\Psi_\mathrm{I}\rangle, \tag{1}$$

where $|\Psi_\mathrm{I}\rangle$ represents the overall wave function of the system, including both atoms and the photon. Here, H_I is the Hamiltonian, and the subscript I indicates that we are working within the interaction picture.

The initial symmetry may be maintained if both atoms partially absorb and then re-emit the photon, similar to a double-slit experiment. This would result in an observable interference pattern[40]. However, to absorb the photon, the symmetry must be broken. The deterministic nature of the Schrödinger equation alone is insufficient to achieve this break in symmetry. When the equation is unable to further evolve the system, it essentially "freezes", leading to:
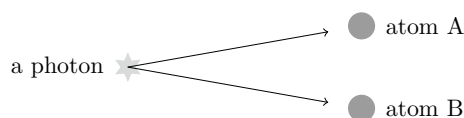

Figure 1. Two atoms interacting with a single photon. The photon initially interacts symmetrically with both atoms but ultimately is absorbed by only one, breaking the symmetry and introducing randomness.

$$i\hbar\frac{d}{dt}|\Psi_\text{I}\rangle = 0. \tag{2}$$

At this point, the overall wave function takes the form:

$$|\Psi_\text{I}\rangle = \frac{1}{\sqrt{2}}|1\rangle_A|0\rangle_B + \frac{1}{\sqrt{2}}|0\rangle_A|1\rangle_B, \tag{3}$$

where $|0\rangle$ and $|1\rangle$ denote the ground and excited states of an atom, respectively. The two atoms are entangled.

We can rewrite Eq. (3) as follows:

$$|\Psi_\text{I}\rangle = \sqrt{2}\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)_A \left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)_B - \frac{1}{\sqrt{2}}|0\rangle_A|0\rangle_B - \frac{1}{\sqrt{2}}|1\rangle_A|1\rangle_B. \tag{4}$$

The coefficient $\sqrt{2}$ in the first term arises due to the non-orthogonality of the three terms. Note that the first term is unique and cannot be represented by any combination of the remaining terms. This term captures a unique feature of the system: both atom A and atom B are at least partially in the intermediate state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. Additionally, while the components $|0\rangle_A|0\rangle_B$ and $|1\rangle_A|1\rangle_B$ may not satisfy the laws of energy conservation, they are permitted to appear for a very short time due to Heisenberg's uncertainty principle[5].

Despite the entanglement between atoms A and B, each atom can still partially behave as if it were an isolated particle in a superposition state. This phenomenon can be further illustrated by the hydrogen atom example. Although the hydrogen atom is a two-body system with the electron and proton positionally entangled, the electron can nonetheless be described by a wave function, such as $\psi_{1,0,0}(r,\theta,\phi)$, as if it were an isolated particle, albeit in a superposition state.

Electrons in atoms occupy discrete eigenstates, resulting in stable wave functions over time scales shorter than the lifetime of spontaneous emission. For example, in a hydrogen atom's 2p state, the electron's density distribution remains time-independent over durations much shorter than the 2p state's nanosecond lifetime.

In contrast, when considering a superposition of discrete eigenstates, the wave function becomes dynamic. Let's consider hydrogen atoms as examples, with their eigenstates represented as follows:

$$|0\rangle = \Psi_{1,0,0}(r,\theta,\phi,t), \quad |1\rangle = \Psi_{2,1,1}(r,\theta,\phi,t), \tag{5}$$

with corresponding energy eigenvalues $E_{1,0,0}$ and $E_{2,1,1}$, respectively. When atom A is in the state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, the wave function is given by:

$$\Psi_A(r,\theta,\phi,t) = \frac{1}{\sqrt{2}}\Psi_{1,0,0}(r,\theta,\phi,t) + \frac{1}{\sqrt{2}}\Psi_{2,1,1}(r,\theta,\phi,t). \tag{6}$$

Consequently, the time-dependent density distribution is:

$$|\Psi_A(r,\theta,\phi,t)|^2 = f_1(r,\theta) + f_2(r,\theta)\cos(\phi - \omega t), \tag{7}$$

where $\omega = \Delta E/\hbar$, or more specifically, $\omega = (E_{2,1,1} - E_{1,0,0})/\hbar$, $\hbar$ is the reduced Planck's constant. This density distribution rotates with an angular frequency ω, potentially leading to an emission of electromagnetic waves or interactions with existing fields. In a physical vacuum, electromagnetic waves may arise due to vacuum fluctuations and may interact with this state. In addition, cosmic microwave background radiation[41] may also play a role.

Wave function collapse induced by vacuum fluctuations

When atom A, in the state described by Eq. (6), interacts with a vacuum fluctuation, its wave function undergoes a change:

$$\Psi_A(r,\theta,\phi,t) \xrightarrow[\text{fluctuation}]{\text{a vacuum}} \sin\phi\,\Psi_{1,0,0}(r,\theta,\phi,t) + \cos\phi\,\Psi_{2,1,1}(r,\theta,\phi,t). \tag{8}$$

A phase difference between the two terms may also exist, but it should not play a major role in this study and is therefore not specified. The energy change from $\frac{1}{2}(E_{1,0,0} + E_{2,1,1})$ to $\sin^2\phi E_{1,0,0} + \cos^2\phi E_{2,1,1}$ necessitates a corresponding change in atom B to conserve energy:

$$\Psi_B(r,\theta,\phi,t) \xrightarrow[\text{fluctuation}]{\text{same vacuum}} \cos\phi\,\Psi_{1,0,0}(r,\theta,\phi,t) + \sin\phi\,\Psi_{2,1,1}(r,\theta,\phi,t). \tag{9}$$

This instantaneous correlation between possibly widely separated atoms is a hallmark of quantum entanglement, initially proposed by Einstein, Podolsky, and Rosen (EPR)[8] and further elaborated by Bell[9]. The entanglement persists from the moment the photon begins interacting with the atoms until one of the atoms completely absorbs the photon, thereby linking the photon absorption process with the creation and destruction of the entanglement between the atoms.

Accordingly, the overall wave function evolves as follows:

$$|\Psi_\text{I}\rangle \xrightarrow[\text{fluctuation}]{\text{vacuum}} \sin\theta|1\rangle_A|0\rangle_B + \cos\theta|0\rangle_A|1\rangle_B, \tag{10}$$

where $\theta = \arctan\cot^2\phi$ and any possible phase difference between the two terms has been omitted. This expression ensures the conservation of energy. However, the Heisenberg uncertainty principle permits brief departures

from the usual rule of energy conservation. This means that the above expression can be temporarily deviated from, allowing the two atoms to interact with vacuum fluctuations independently for a short time. Eventually, these independent interactions reconcile to ensure energy conservation over a longer timescale.

The entanglement between the two atoms suggests the presence of faster-than-light correlations. Interestingly, this faster-than-light feature is also present within each individual atom. As described by Eqs. (6) and (7), the electron cloud extends infinitely, giving the appearance of superluminal rotation in its outer regions. However, this does not violate causality, as the electron cloud represents a single quantized entity rather than a multi-particle system. Causality is preserved as long as the speed at which the wave function propagates to regions where it previously had zero amplitude, from the nearest region with non-zero amplitude, does not exceed the speed of light.

Another feature is that vacuum fluctuations enable a smooth process for completing the photon absorption. As the system approaches an eigenstate, the factor $f_2(r, \theta)$ in Eq. (7) decreases, weakening the interaction with vacuum fluctuations. This results in a gradual slowing down of the dynamic process, ensuring that the dynamic process is continuous even at its conclusion. This phenomenon can be further studied using an analogy with Brownian motion.

Like the CSL model[31], our example faces a "tail problem," but in the temporal dimension, characterized by indefinite photon absorption duration. It's worth noting that some processes in physics, such as the formation of a hydrogen atom, inherently demand an infinite duration to comply with causality. For instance, an electron transitioning from a spatially confined state to an eigenstate, such as $\Psi_{1,0,0}(r, \theta, \phi, t)$, which extends to infinity, must take an infinite amount of time. In light of this, the temporal tail problem in our example doesn't pose a fundamental issue. Its experimental impact is minimal because the effect diminishes exponentially over time, making it practically negligible. In fact, this exponential decrease is so rapid that, on the scale of physical experiments, the entire process appears to occur almost instantaneously.

Brownian motion analogy for disentanglement

For the example illustrated in Fig. 1, the disentanglement begins when the overall wave function is in the state described by Eq. (3). In a more general scenario where the two atoms are not arranged symmetrically, the system's wave function, when it is stuck, takes the following form:

$$|\Psi_I\rangle = C_1 |1\rangle_A |0\rangle_B + C_2 |0\rangle_A |1\rangle_B, \tag{11}$$

where C_1 and C_2 are complex probability amplitudes that satisfy $|C_1|^2 + |C_2|^2 = 1$. We define a parameter x such that

$$|C_1|^2 = x, \quad |C_2|^2 = 1 - x. \tag{12}$$

The disentanglement process in this general case can be likened to a particle undergoing continuous Brownian motion[42] on a unit-length line, starting at position x, as depicted in Fig. 2. The particle reaching the endpoints 0 and 1 corresponds to the disentanglement outcomes $|0\rangle_A |1\rangle_B$ and $|1\rangle_A |0\rangle_B$, respectively. To model the slowing down of the disentanglement near eigenstates, we introduce a diffusion coefficient[43] $D(x) = x(1 - x)$. Consequently, the diffusion velocity of the particle is given by:

$$v(x) \propto x(1 - x). \tag{13}$$

In other words, as the particle approaches an endpoint, either 0 or 1, its motion slows down, ensuring a smooth and continuous end to the Brownian motion.

To be consistent with Born's rule[6], the probability of the particle reaching endpoint 1 should be x, and the probability of reaching endpoint 0 should be $1 - x$. The Born rule can be reproduced. We show this in the following way. When the particle starts at a position $\xi < \frac{1}{2}$, it has an equal probability of reaching either 0 or 2ξ, provided the Brownian motion does not favor one direction over the other. This remains true even if the diffusion coefficient $D(x)$ is not constant. When the particle starts at a position $\xi > \frac{1}{2}$, it has an equal probability of reaching either 1 or $2\xi - 1$. By combining these two scenarios, we can study Brownian motion starting at any position x.

To reproduce the Born's rule, we expand x ($0 \leq x \leq 1$) as follows:

$$x = c_1 \frac{1}{2} + c_2 \left(\frac{1}{2}\right)^2 + \cdots + c_n \left(\frac{1}{2}\right)^n + \cdots, \tag{14}$$

where each of $c_1, c_2, \ldots, c_n, \ldots$ is either 0 or 1. This representation aligns with the binary representation of a fraction that is less than 1. Using this representation, we can calculate the probability of the particle reaching endpoint 1 by following the flowchart in Fig. 3. The flowchart demonstrates that the probability of the particle reaching endpoint 1 is x. This method of reproducing Born's rule is similar to the gambler's ruin mechanism[30,31].

Figure 2. Brownian motion on a line of unit length, where a particle starts at position x. The probability of the particle reaching endpoint 1 is x, while the probability of the particle reaching endpoint 0 is $1 - x$.
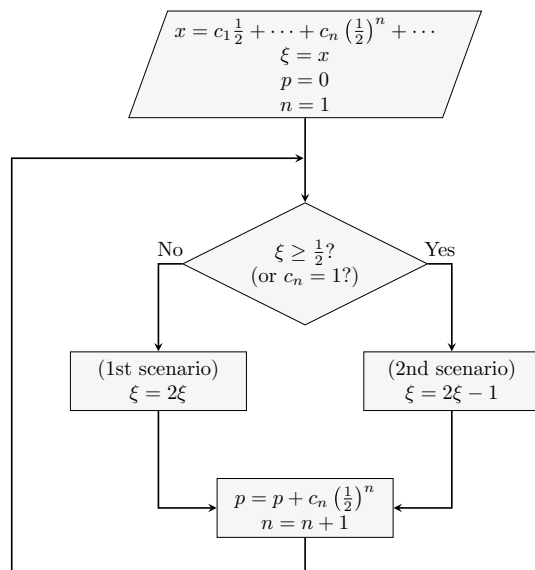
$$x = c_1 \frac{1}{2} + \cdots + c_n \left(\frac{1}{2}\right)^n + \cdots$$
$$\xi = x$$
$$p = 0$$
$$n = 1$$

$\xi \geq \frac{1}{2}?$
(or $c_n = 1$?)

No   Yes

(1st scenario)
$\xi = 2\xi$

(2nd scenario)
$\xi = 2\xi - 1$

$$p = p + c_n \left(\frac{1}{2}\right)^n$$
$$n = n + 1$$

Figure 3. The flowchart depicting the process of a particle undergoing Brownian motion with an initial position x. It shows that the probability p of the particle reaching endpoint 1 is equal to x, the initial position of the particle.

Model validation

The impact of vacuum fluctuations on photon absorption by two atoms, as shown in Fig.1, can be experimentally probed using the Casimir effect[37,38]. If vacuum fluctuations are crucial for completing photon absorption, this process would be characterized by time-dependence and modulation influenced by fluctuation intensity. The Casimir effect demonstrates that this intensity can be controlled by adjusting the proximity of parallel conductive plates; reducing the gap results in weakened fluctuations. In an adapted setup, positioning these plates around the two atoms from Fig.1 could prolong their entanglement. During this extended entanglement, the atoms have a non-zero probability of simultaneously re-emitting the photon, resulting in an observable interference pattern akin to a double-slit experiment[40]. The observation window for this pattern, or the time duration over which the interference occurs, can be measured. If vacuum fluctuations are indeed responsible for disrupting the entanglement, then a correlation should exist: the closer the plates, the wider the observation window. This provides a foundation for experimental validation.

Additionally, this experimental setup could further validate our proposed mechanism. Following photon absorption, spontaneous emission, as per our model, would not produce a two-slit interference pattern but rather a single-slit diffraction pattern, attributed to the photon being absorbed by a single atom. Therefore, while observations within the excitation window are expected to show a double-slit pattern, a shift to a single-slit pattern is predicted post-excitation. This transition contrasts with standard quantum mechanics predictions. Drawing from Schrödinger's cat thought experiment[7], which posits that unobserved states maintain coherence, interpreting the superposition in Eq. (3) as a Schrödinger's cat state implies that coherence would persist through photon absorption and into the spontaneous emission phase, resulting in ongoing two-slit interference. This deviation can be leveraged to test our mechanism by observing whether there is a shift from a two-slit to a single-slit interference pattern, depending on the timing relative to the initiation of photon absorption. For accurate results, it is crucial to ensure that the excited state's lifetime significantly surpasses the duration of excitation.

Three-atom photon absorption

A similar study can be carried out for scenarios in which a single photon is absorbed by more than two atoms. In a three-atom scenario, as depicted in Fig. 4, the wave function $|\Psi_I\rangle$ assumes the following form when it is stuck:

$$|\Psi_I\rangle = C_1|1\rangle_A|0\rangle_B|0\rangle_C + C_2|0\rangle_A|1\rangle_B|0\rangle_C + C_3|0\rangle_A|0\rangle_B|1\rangle_C, \tag{15}$$
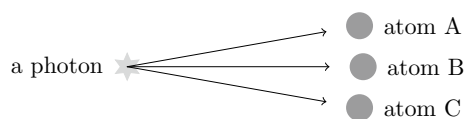

a photon   atom A

atom B

atom C

Figure 4. A photon interacting with three atoms, eventually being absorbed by one of them.

where C_1, C_2, and C_3 are complex probability amplitudes that satisfy $|C_1|^2 + |C_2|^2 + |C_3|^2 = 1$. The three atoms are entangled. We define x_1 and x_2 as follows:

$$|C_1|^2 = x_1, \quad |C_2|^2 = x_2 - x_1, \quad |C_3|^2 = 1 - x_2. \tag{16}$$

The disentanglement can be likened to two particles undergoing Brownian motion on the same unit length line, starting at positions x_1 and x_2 respectively, as depicted in Fig. 5. Upon collision, the particles merge. There are three possible outcomes:

- Both reach endpoint 1, with probability x_1.
- Both reach endpoint 0, with probability $1 - x_2$.
- One at each endpoint, with probability $x_2 - x_1$.

The disentanglement leads to one of the following states:

- $|1\rangle_A|0\rangle_B|0\rangle_C$, with probability x_1, or $|C_1|^2$.
- $|0\rangle_A|0\rangle_B|1\rangle_C$, with probability $1 - x_2$, or $|C_3|^2$.
- $|0\rangle_A|1\rangle_B|0\rangle_C$, with probability $x_2 - x_1$, or $|C_2|^2$.

This framework can be generalized to include more atoms by adding additional particles, while still employing the same Brownian motion analogy.

One-atom photon absorption

A single atom in a superposition of discrete states $|0\rangle$ and $|1\rangle$ may also interact with vacuum fluctuations. To illustrate this, consider a scenario with only one atom absorbing a photon. Initially, the system's wave function is $|\gamma\rangle|0\rangle$, where $|\gamma\rangle$ denotes the wave function of the photon. Upon interaction, the wave function evolves to:

$$|\Psi_I\rangle = C_1|\gamma\rangle|0\rangle + C_2|1\rangle, \tag{17}$$

where C_1 and C_2 satisfy $|C_1|^2 + |C_2|^2 = 1$. Rewriting this equation yields:

$$|\Psi_I\rangle = (|\gamma\rangle + 1)(C_1|0\rangle + C_2|1\rangle) - C_1|0\rangle - C_2|\gamma\rangle|1\rangle. \tag{18}$$

The atom is partially in the superposition state $C_1|0\rangle + C_2|1\rangle$, enabling it to interact with vacuum fluctuations. This introduces randomness: vacuum fluctuations may occasionally prevent the photon from being absorbed and alter its wave function in such a way that it goes out into a random direction.

This example could be considered a special case of the CSL model and vacuum fluctuations could serve as the random term. However, this random term is likely to be significant only when the atom is in a superposition state.

Extending this example to multi-atom systems, such as the one depicted in Fig. 1, suggests that vacuum fluctuations should initiate as soon as atoms enter a superposition. The overall wave function then becomes:

$$|\Psi_I\rangle = C_1|\gamma\rangle|0\rangle_A|0\rangle_B + C_2|1\rangle_A|0\rangle_B + C_3|0\rangle_A|1\rangle_B, \tag{19}$$

with C_1, C_2, C_3 satisfying $|C_1|^2 + |C_2|^2 + |C_3|^2 = 1$. The Schrödinger equation and vacuum fluctuations govern the system's evolution simultaneously as soon as the interaction starts. Specifically, while the Schrödinger equation governs the transition from the first term to the second and third terms, vacuum fluctuations cause the coefficients C_1, C_2, and C_3 to fluctuate.

Information and vacuum fluctuations

In the absence of vacuum fluctuations, the complete absorption of a photon by an atom would be impossible. Governed solely by the deterministic Schrödinger equation, this process would require the photon's wave function to align precisely with the atom's discrete eigenstates to facilitate transitions. However, given that the photon's wave function possesses a continuous spatial configuration established prior to its interaction with the atom, there is an inherently near-zero probability of achieving such precise alignment.

Vacuum fluctuations offer a solution to these issues by facilitating the transition from the initial to the final state through two concurrent ways:

- The Schrödinger equation maps the initial state-which includes both the photon and the atom in its ground state-to an output that closely approximates one of the atom's excited states. Any deviations manifest as vacuum fluctuations, which eventually decouple from the excited state, preserving unrepresented information
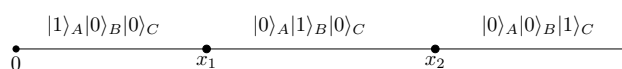

Figure 5. Two particles undergoing Brownian motion on a line of unit length. Upon collision, the two particles merge into a single particle.

from the initial state. It's worth noting that this preserved information is not readily extractable and remains hidden. Additionally, treating the output as a superposition of the excited state and vacuum fluctuations is valid only when all conservation laws are met.

- Most of the time, the Schrödinger equation maps the initial state to an output that is a general superposition of the ground and excited states. Pre-existing vacuum fluctuations induce Brownian motion in this output state, steering it closer to an eigenstate.

Our study suggests that vacuum fluctuations could be central to explaining the randomness observed in the photon absorption process by atoms. These fluctuations, integral to quantum field theory, are essential for accurately calculating phenomena such as the Lamb shift[44,45]. Yet, the deterministic nature of quantum field theory poses an intriguing paradox: how does it give rise to randomness in photon absorption? Quantum field theory's role in time evolution implies that vacuum fluctuations are dynamic, a notion visually exemplified in Quantum Chromodynamics (QCD)[46,47]. Different from the Lamb shift, photon absorption is a dynamic process and can be influenced by the evolving nature of vacuum fluctuations. Should these fluctuations indeed be dynamic, their specific initial conditions could hold latent information that manifests as apparent randomness during the photon absorption process, as guided by the dynamics of quantum field theory. This phenomenon mirrors the principles of chaos theory[48], effectively bridging deterministic and probabilistic frameworks in physics.

Summary

We have investigated scenarios involving the absorption of a single photon by one, two, and three atoms to address several fundamental issues. Firstly, we demonstrate that this process can be continuous, with the Schrödinger equation playing a significant role in its time evolution. Secondly, vacuum fluctuations are shown to contribute to this evolution, introducing randomness. Thirdly, by exploring single-system scenarios instead of ensembles, we successfully replicate the Born rule in this context through a Brownian motion analogy. Fourthly, the challenge posed by the discrete nature of atomic eigenstates implies that external forces must intervene, leading to information loss and the emergence of randomness. Additionally, we propose an experiment to investigate the impact of vacuum fluctuations on two atoms absorbing a single photon in a double-slit setup, with the atoms acting as slits. This experiment aims to ascertain whether the Casimir effect can prolong the timeframe for creating a two-slit interference pattern.

Data availability

All data generated or analysed during this study are included in this published article.

References

1. Scully, M. O. & Zubairy, M. S. *Quantum Optics* (Cambridge University Press, 1997).
2. Shankar, R. *Principles of Quantum Mechanics* (Springer, 1994).
3. Rudin, W. *Real and Complex Analysis 3rd* ed. (McGraw-Hill, 1987).
4. Bohr, N. The quantum postulate and the recent development of atomic theory1. *Nature* **121**(3050), 580–590. https://doi.org/10.1038/121580a0 (1928).
5. Heisenberg, W. Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. *Z. Phys.* **43**(3), 172–198. https://doi.org/10.1007/BF01397280 (1927).
6. Born, M. Quantenmechanik der Stoßvorgänge. *Z. Phys.* **38**(11), 803–827. https://doi.org/10.1007/BF01397184 (1926).
7. Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften* **23**(48), 807–812. https://doi.org/10.1007/BF01491891 (1935).
8. Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete?. *Phys. Rev.* **47**(10), 777–780. https://doi.org/10.1103/PhysRev.47.777 (1935).
9. Bell, J. S. On the Einstein Podolsky Rosen paradox. *Phys. Phys. Fizika* **1**(3), 195–200. https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195 (1964).
10. de Broglie, L. La mécanique ondulatoire et la structure atomique de la matière et du rayonnement. *J. Phys. Radium* **8**(5), 225–241. https://doi.org/10.1051/jphysrad:0192700805022500 (1927).
11. Bohm, D. A suggested interpretation of the quantum theory in terms of Hidden variables. I. *Phys. Rev.* **85**(2), 166–179. https://doi.org/10.1103/PhysRev.85.166 (1952).
12. Bricmont, J. *Making Sense of Quantum Mechanics Softcover Reprint of the Hardcover* 1st edn. (Springer International Publishing, 2016).
13. Everett, H. Relative state formulation of quantum mechanics. *Rev. Modern Phys.* **29**(3), 454–462. https://doi.org/10.1103/RevModPhys.29.454 (1957).
14. Saunders, S. *et al.* (eds) *Many Worlds?: Everett, Quantum Theory, & Reality* (Oxford University Press, 2010).
15. Zeh, H. D. On the interpretation of measurement in quantum theory. *Found. Phys.* **1**(1), 69–76. https://doi.org/10.1007/BF00708656 (1970).
16. Zurek, W. H. Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse?. *Phys. Rev. D* **24**(6), 1516–1525. https://doi.org/10.1103/PhysRevD.24.1516 (1981).
17. Joos, E. *et al. Decoherence and the Appearance of a Classical World in Quantum Theory* (Springer, 2003).
18. Zurek, W. H. Decoherence, einselection, and the quantum origins of the classical. *Rev. Mod. Phys.* **75**(3), 715–775. https://doi.org/10.1103/RevModPhys.75.715 (2003).
19. Schlosshauer, M. Decoherence, the measurement problem, and interpretations of quantum mechanics. *Rev. Mod. Phys.* **76**(4), 1267–1305. https://doi.org/10.1103/RevModPhys.76.1267 (2005).
20. Schlosshauer, M. Quantum decoherence. *Phys. Rep.* **831**, 1–57. https://doi.org/10.1016/j.physrep.2019.10.001 (2019).
21. Ghirardi, G. C., Rimini, A. & Weber, T. Unified dynamics for microscopic and macroscopic systems. *Phys. Rev. D* **34**(2), 470–491. https://doi.org/10.1103/PhysRevD.34.470 (1986).

22. Diósi, L. Models for universal reduction of macroscopic quantum fluctuations. *Phys. Rev. A* **40**(3), 1165–1174. https://doi.org/10.1103/PhysRevA.40.1165 (1989).
23. Bassi, A. & Ghirardi, G. Dynamical reduction models. *Phys. Rep.* **379**(5), 257–426. https://doi.org/10.1016/S0370-1573(03)00103-0 (2003).
24. Carlesso, M. & Donadi, S. Vacchini, B., Breuer, H.-P. & Bassi, A. Collapse models: Main properties and the state of art of the experimental tests. In *Advances in Open Systems and Fundamental Tests of Quantum Mechanics, Springer Proceedings in Physics* (eds. Vacchini, B. et al.) 1–13 (Springer International Publishing, 2019).
25. Pearle, P. Combining stochastic dynamical state-vector reduction with spontaneous localization. *Phys. Rev. A* **39**(5), 2277–2289. https://doi.org/10.1103/PhysRevA.39.2277 (1989).
26. Ghirardi, G. C., Pearle, P. & Rimini, A. Markov processes in Hilbert space and continuous spontaneous localization of systems of identical particles. *Phys. Rev. A* **42**(1), 78–89. https://doi.org/10.1103/PhysRevA.42.78 (1990).
27. Bassi, A., Lochan, K., Satin, S., Singh, T. P. & Ulbricht, H. Models of wave-function collapse, underlying theories, and experimental tests. *Rev. Mod. Phys.* **85**(2), 471–527. https://doi.org/10.1103/RevModPhys.85.471 (2013).
28. Carlesso, M., Bassi, A., Falferi, P. & Vinante, A. Experimental bounds on collapse models from gravitational wave detectors. *Phys. Rev. D* **94**(12), 124036. https://doi.org/10.1103/PhysRevD.94.124036 (2016).
29. Einstein, A. Zur quantentheorie der strahlung. *Phys. Zeitschr.* **18**, 121–128. https://doi.org/10.1017/S0370164600034429 (1917).
30. Pearle, P. Might god toss coins?. *Found. Phys.* **12**(3), 249–263. https://doi.org/10.1007/BF00726850 (1982).
31. Pearle, P. Tales and tails and stuff and nonsense. In *Experimental Metaphysics-Quantum Mechanical Studies in Honor of Abner Shimony*, Vol. 1 (eds. Cohen, R. S. et al.) 143–156 (Kluwer, 1997). https://arxiv.org/abs/quant-ph/9805050.
32. Bohr, N. On the constitution of atoms and molecules, part I. *Phil. Mag.* **26**, 1–25 (1913).
33. Griffiths, D. J. *Introduction to Quantum Mechanics* 2nd edn. (Cambridge University Press, 2017).
34. Feynman, R. P. *Quantum Electrodynamics Advanced Book Classics* (CRC Press, 2018).
35. Milonni, P. W. & Smith, W. A. Radiation reaction and vacuum fluctuations in spontaneous emission. *Phys. Rev. A* **11**(3), 814–824. https://doi.org/10.1103/PhysRevA.11.814 (1975).
36. Milonni, P. W. Why spontaneous emission?. *Am. J. Phys.* **52**(4), 340–343. https://doi.org/10.1119/1.13886 (1984).
37. Casimir, H. B. G. & Polder, D. The influence of retardation on the London-van der Waals forces. *Phys. Rev.* **73**(4), 360–372. https://doi.org/10.1103/PhysRev.73.360 (1948).
38. Lamoreaux, S. K. Demonstration of the Casimir force in the 0.6 to 6 Mm range. *Phys. Rev. Lett.* **78**(1), 5–8. https://doi.org/10.1103/PhysRevLett.78.5 (1997).
39. Bragg, W. H. & Bragg, W. L. The reflection of X-rays by crystals. *Proc. R. Soc. Lond. Ser. A, Contain. Pap. Math. Phys. Char.* **88**(605), 428–438. https://doi.org/10.1098/rspa.1913.0040 (1997).
40. Eichmann, U. *et al.* Young's interference experiment with light scattered from two atoms. *Phys. Rev. Lett.* **70**(16), 2359–2362. https://doi.org/10.1103/PhysRevLett.70.2359 (1993).
41. Penzias, A. A. & Wilson, R. W. A measurement of excess antenna temperature at 4080 Mc/s. *Astrophys. J.* **142**, 419–421. https://doi.org/10.1086/148307 (1965).
42. Hänggi, P. & Marchesoni, F. Introduction: 100years of Brownian motion. *Chaos Interdiscipl. J. Nonlinear Sci.* **15**(2), 026101. https://doi.org/10.1063/1.1895505 (2005).
43. Bhattacharyay, A. Equilibrium of a Brownian particle with coordinate dependent diffusivity and damping: Generalized Boltzmann distribution. *Phys. A* **515**, 665–670. https://doi.org/10.1016/j.physa.2018.10.017 (2019).
44. Lamb, W. E. & Retherford, R. C. Fine structure of the hydrogen atom by a microwave method. *Phys. Rev.* **72**(3), 241–243. https://doi.org/10.1103/PhysRev.72.241 (1947).
45. Bethe, H. A. The electromagnetic shift of energy levels. *Phys. Rev.* **72**(4), 339–341. https://doi.org/10.1103/PhysRev.72.339 (1947).
46. Wilczek, F. Asymptotic freedom: From paradox to paradigm. *Proc. Natl. Acad. Sci.* **102**(24), 8403–8413. https://doi.org/10.1073/pnas.0501642102 (2005).
47. University of Adelaide. Visualizations of Quantum Chromodynamics. http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/ (2023).
48. Lorenz, E. N. Deterministic nonperiodic flow. *J. Atmos. Sci.* **20**(2), 130–141. https://doi.org/10.1175/1520-0469 (1963).

Acknowledgements

Author contributions

Y.Z. is the sole author.

Competing interests

The author declares no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Y.Z.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.