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Research Article

Relation between Quantum Jump and Wave Function Collapse

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Whether the wave function collapses or not is a major remaining question in the theory of quantum measurement. This difficulty stems from the following two facts. First, it has not been recognized that single-particle quantum mechanics and many-particle quantum mechanics must be treated separately. Second, quantum jump (QJ) and wave function collapse (WFC) need clearer definitions. We define a QJ as a process of selecting a set of system eigenvalues (SEVs) of an observable and a WFC as a process of determining the probability distribution (PD) of SEVs, both from a single measurement. The goal of quantum observation is to obtain the PD, which is determined from an ensemble of SEVs. The wave function becomes an observable when the PD is determined. In single-particle quantum mechanics, a single measurement results in only one set of SEVs, and the PD is not observable. Therefore, the WFC does not happen. In many-particle quantum mechanics, we focus on the occupation number of a single quantum state. The wave function does not collapse in general, but there are exceptions. The occupation number can be huge and macroscopic for photons or for Bose-Einstein condensates. In such a case, the PD is determined from a single measurement of a real ensemble, and the WFC occurs. We call it a macroscopic quantum jump, which effectively is a measurement of a classical observable.

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I. Introduction

Nearly a century has passed since the birth of quantum mechanics, and yet the measurement problem has not been fully solved. One major remaining question is whether the wave function collapses or not.

In a previous paper (Paper I[1]), we have given an interpretation of single-particle quantum mechanics, which elucidates a quantum jump (QJ) to be a jump from microscopic to microscopic. We call this process a microscopic quantum jump (MIJ). This MIJ interpretation better defines the QJ and allows a clearer distinction between QJ and wave function collapse (WFC). Until recently, the QJ and the WFC were treated as the same thing, but here we distinguish them clearly.

First, we define a QJ as a process of selecting a set of system eigenvalues (SEVs) of an observable. It is an experimental entity determined from a single measurement. On the other hand, the wave function (WF) is a theoretical notion associated with a probability distribution (PD) of quantum states. Now we define a WFC to be a phenomenon associated with a single measurement. For single-particle quantum mechanics, the PD is obtained from repeated measurements. A single event does not tell anything about the PD, and therefore the WF does not collapse. In Section II, we present representative experiments of single-particle quantum mechanics in which the WFC does not happen.

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How about many-particle quantum mechanics? In general, the situation is the same as that for single-particle quantum mechanics. However, there are some interesting exceptions in which the WFC happens due to a large occupation number of a quantum state. For these cases, quantum states are macroscopic, and the wave function is for a superposition of these macroscopic quantum states. Therefore, a single measurement yields a PD, and WFC is realized. We discuss many-particle quantum mechanics in Section III. The implication of our results is discussed in Section IV.

II. Single-particle quantum mechanics

A. Summary of microscopic quantum jump interpretation

In a previous paper (Paper I), we have introduced a new interpretation of the measurement problem in single-particle quantum mechanics. Here we briefly summarize this interpretation. Since von Neumann[2], a single quantum system was implicitly supposed to interact with enormously many degrees of freedom in an apparatus, but we do not think this is the case. We have shown that a single quantum system interacts with only one particle in an apparatus at a time as a quantum jump (QJ). This jump emits a microscopic particle (MIP) which carries the information of system eigenvalues (SEVs) potentially. We call this process a microscopic quantum jump (MIJ). After the MIJ, there are two possible paths toward the SEVs becoming macroscopic. One path is amplification, in which the MIP triggers the multiplication of secondary particles which eventually produces a macroscopic observable (MAO) carrying the information of the SEVs in actuality. One measurement is complete when a MAO is obtained. The experiment continues until an ensemble of MAOs is collected and a probability distribution (PD) of SEVs is obtained from the statistics of MAOs. The other path is the accumulation of the MIPs to obtain the statistics of the SEVs directly. In this case, an ensemble of the SEVs or MAOs is obtained without forming a MAO from each event. The amplification is outside the domain of single-particle quantum mechanics because it occurs after the MIJ. Accumulation is also outside the domain of single-particle quantum mechanics because each MIP is generated as a result of one MIJ.

In Paper I, we did not ask about the mechanism of the MIJ, since we cannot investigate it by experiments, following the attitude of Dirac[3](p.6). Although we still consider that the argument of Dirac is valid, now it seems that we can be more specific about the MIJ in relation to the WFC. In this paper, we discuss the distinction and relation between the MIJ and the WFC by focusing on the meaning of the PD. The MIJ is strictly true for single-particle quantum mechanics, and we will discuss many-particle quantum mechanics later in Section III.

B. PD obtained from a virtual ensemble: Two-dimensional photon-counting detection

As we have already mentioned, a MIJ is a process of selecting a set of SEVs of an observable, but not a collapse of the wave function. We will clarify this point by introducing concrete examples.

Let us consider a double-slit experiment using a two-dimensional photon-counting detector. At low light levels, individual photons arrive at the detector surface sequentially. Details of this kind of experiment are described in Paper I.

What we observe as a MAO for one photon event is a two-dimensional position (x, y) plus an arrival time t. (x, y) are a set of SEVs related to an interference pattern, while t is not related to the interference pattern. At this point, we have no information on the observed PD, $\mathrm{P}_{\mathrm{O}}(x, y)$. It is not clear if we should interpret this MIJ as a collapse of the wave function because a wave function ψ is a quantity related to a theoretical PD, $\mathrm{P}_{\mathrm{T}}(x, y)$= $\psi^*(x, y)\psi(x, y)$, which should be compared with an observed PD, $\mathrm{P}_{\mathrm{O}}(x, y)$.

$\mathrm{P}_{\mathrm{O}}(x, y)$ becomes an observable from an ensemble of (x, y)s after integrating MAOs in time t. Individual photon events follow the fixed PD, $\mathrm{P}_{\mathrm{O}}(x, y)$., but we cannot tell anything about $\mathrm{P}_{\mathrm{O}}(x, y)$, only from one event. An observed $\mathrm{P}_{\mathrm{O}}(x, y)$ and a theoretical $\mathrm{P}_{\mathrm{T}}(x, y)$ are to be compared by an experiment, which collects an ensemble of SEVs. The simplest interpretation of this situation is that the theoretical PD, $\mathrm{P}_{\mathrm{T}}(x, y)$ is the same for each MIJ, and also the WF $\psi(x, y)$ is the same for each MIJ, and they do not collapse.

This ensemble interpretation of $\psi(x, y)$ is a primitive form of second quantization[4](p.106), since $\Psi(x, y) = \sqrt{\mathrm{N}(x, y)}\psi(x, y)$ becomes an observable or q-number, where $\mathrm{N}(x, y)$ is the number of photon events at (x, y) in the interference pattern and $\mathrm{N}(x, y) = \Psi^\dagger(x, y)\Psi(x, y)$. Since $\mathrm{N}(x, y)$ is obtained from repeated measurements of MAOs, this ensemble is a virtual ensemble.

C. PD obtained from an integrated real ensemble: Photon detection by a CCD

Now we consider a double-slit experiment using an integration-type detector such as a CCD, which is described in detail in Paper I. In order to obtain an observed PD, $\mathrm{P_O}(x, y)$, it is not always necessary to count individual photon events as MAOs. Instead, one can accumulate photoelectrons as MIPs at each pixel at (x, y) until the number of MIPs becomes macroscopic. A photon is absorbed at one pixel, and a photoelectron is generated as a MIP by the internal photoelectric effect. However, this MIP does not trigger amplification and stays at that pixel. The MIJ is a selection of the pixel location (x, y) and this process follows $\mathrm{P_O}(x, y)$. After accumulating MIPs at pixel (x, y), the number of MIPs, $\mathrm{N}(x, y)$ becomes a MAO. $\mathrm{P_O}(x, y)$ becomes an observable from the MAOs at all pixels. $\mathrm{N}(x, y)$ at all pixels is obtained from a real ensemble after the accumulation.

Is there any difference between photon counting detection and photon detection by a CCD in terms of a MIJ? One MIJ is a selection of SEVs or (x, y) obeying the PD $\mathrm{P_O}(x, y)$. All MIJs follow the same $\mathrm{P_O}(x, y)$, and there is no point in assuming collapses of $\mathrm{P_O}(x, y)$. Photon counting detection and photon detection by a CCD are the same until a photoelectron that carries the information of SEVs is generated. Although there is a difference between amplification and accumulation, they are outside the domain of single-particle quantum mechanics, since quantum mechanics covers up to the stage of emission of a MIP.

$\mathrm{P_T}(x, y)$ (perfect interference pattern) and $\mathrm{P_O}(x, y)$ can be compared only after an ensemble of SEVs has been obtained. $\Psi(x, y) = \sqrt{\mathrm{N}}\psi(x, y)$ becomes a q-number only when we compare these PDs. There is no point in considering a collapse of the wave function for each MIJ.

D. α decay in a Wilson cloud chamber

We now consider α decay of U^{238} placed in a Wilson cloud chamber (WCC). A U^{238} nucleus decays into a Th^{234} nucleus, which stays in the source, and an α particle, which is emitted from the source. Theoretically, the α decay is described by an S wave, and it was once considered that the linear tracks seen in the WCC were a contradiction to the S-wave wave function because ionization would appear randomly in space for the S wave. We show here that this is not a contradiction from the point of view that WFC does not occur in single-particle quantum mechanics.

We begin with the following thought experiment. We imagine a spherical vacuum chamber whose inner surface is sensitive to the point of arrival of an α particle. The α particle source is placed at the center of the sphere, whose radius is R. We set polar coordinates (r, θ, ϕ) with the origin at the center of the sphere. We consider the detection of a series of α particles to obtain an ensemble of the positions of arrival, (R, θ, ϕ)s as SEVs to form a PD, $\mathrm{P_O}(R, \theta, \phi)$. Theoretically, the S-wave wave function implies an isotropic PD, $\mathrm{P_T}(R)$ or a uniform distribution on the inner surface. As the statistics of SEVs improve, $\mathrm{P_O}(R, \theta, \phi)$ will approach $\mathrm{P_T}(R)$. A single measurement of (R, θ, ϕ) does not tell us anything about $\mathrm{P_O}(R, \theta, \phi)$ as we have seen so far for single-particle quantum mechanics, and WFC does not occur.

We move on to the WCC. In Paper I, we have discussed the detection of an ionization track of an α particle in a WCC. The WCC contains air and supersaturated water vapor. The ionization of an air molecule generates an ion of the air molecule and an electron. Since the electron is driven away, the molecular ion keeps the information of the passage of the α particle. One ionization is one MIJ, and the resultant molecular ion is a MIP, around which water molecules condense to form a macroscopic water droplet. The condensation of water molecules is the amplification process, and the resultant droplet is a MAO. We interpret the ionization track as a result of a series of position measurements of the droplets carrying the information of the passage of the α particle. In a sense, the track is an ensemble of the positions of the α particle.

We now consider the α decay of U^{238} placed in the WCC, which emits an α particle with a kinetic energy of about 5 MeV. For standard temperature and pressure, the number density of air molecules is $n = 2.7 \times 10^{19}$ cm^{-3} and the ionization cross section of a $\mathrm{N_2}$ molecule (the major constituent of air) by an α particle[5] with a kinetic energy of 5 MeV is $\sigma = 5 \times 10^{-16}\mathrm{cm}^2$. The mean free path before one ionization occurs is $x = 1/n\sigma = 7 \times 10^{-5}\mathrm{cm}$. The size of the ionization cross section can be interpreted in the following manner. When the α particle is far away from a $\mathrm{N_2}$ molecule, $\mathrm{N_2}$ is neutral, and the Coulomb force of the α particle has no effect. Only when the α particle approaches the proximity of the $\mathrm{N_2}$ molecule, whose size is a few Å$= 10^{-8}\mathrm{cm}$, does the effect of the Coulomb force become significant. This is why $\sqrt{\sigma}$ is on the order of a few Å. We see a long linear track because of the following two numbers. First, the ratio of $\sqrt{\sigma}/x$ is $10^{-4} \ll 1$ and therefore the track is linear. Second, the ratio of the ionization potential of a $\mathrm{N_2}$ molecule (15 eV)

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to the kinetic energy of the α particle (5 MeV) is $3 \times 10^{-6} \ll 1$ and therefore the track is very long. The wave function for the α particle is a wave packet. Since the kinetic energy of the α particle is much greater than the ionization potential of the air molecule, each ionization is a very small perturbation to the wave packet. So the collapse of the wave packet does not occur for each ionization (MIJ). Simultaneously, SEVs (θ, ϕ) do not change for each track.

In real life, a WCC is not spherical. However, here we consider a spherical WCC by filling the vacuum of the aforementioned spherical detector with air and supersaturated water vapor. We consider the relation between linear tracks and the theoretical S-wave expectation. In the absence of air and supersaturated water vapor, no track will be seen, and the isotropic PD $\mathrm{P_T}(R)$ is expected on the inner surface of the sphere. In the presence of air and supersaturated water vapor (or in the WCC), we will start to see the inner edge of a track at around one mean free path, $r = x = 7 \times 10^{-5}$ cm from the center.

Here we consider the measurements of SEVs or (θ, ϕ)s in two ways. First, if the inner radius R is much greater than one mean free path x, but smaller than the lengths of typical linear tracks, the positions of arrival (R, θ, ϕ)s as SEVs can be measured. However, we have to assume the availability of the imaginary spherical detector. Second, since the tracks are linear, the angles (θ, ϕ)s of individual tracks can be measured, and $\mathrm{P_O}(1, \theta, \phi)$ can be constructed from an ensemble of (θ, ϕ)s on a unit sphere. If the S-wave theory is correct, $\mathrm{P_O}(1, \theta, \phi)$ will approach isotropic $\mathrm{P_T}(1)$ as the statistics improve. This way, the S-wave theory and linear tracks are reconciled by the thought experiment of the spherical WCC.

III. Many-particle quantum mechanics

We have seen that a QJ or a MIJ is not a WFC for single-particle quantum mechanics. The essential point of single-particle quantum mechanics is that the observed PD, $\mathrm{P_O}$ is not an observable for a single measurement. Now we examine the situation in many-particle quantum mechanics by considering the occupation number of a quantum state.

A. Fermions

The occupation number for a fermion state N_f is either 0 or 1. So ordinary fermions do not have macroscopic N_f and the observed PD, $\mathrm{P_O}$ cannot be obtained from a single measurement. The PD must be obtained from repeated measurements or from a virtual ensemble. Formation of a macroscopic quantum state is prohibited by the Pauli exclusion principle. For fermions in general, WFC does not happen.

B. Bosons

The occupation number for a boson state N_b is 0, 1, 2, ..., ∞. So light bosons can have macroscopic N_b and the observed PD, $\mathrm{P_O}$ can be an observable for a single measurement. Since photons are massless and their chemical potential is zero, photons can condense into many photon states and effectively form a classical electromagnetic wave. Liquid He^4 condenses into a superfluid at low temperatures[6][7], and π-on condensation may occur in neutron stars[8]. These are Bose-Einstein condensates. For these bosons, a superposition of macroscopic states can occur, and the PD can be obtained from a single measurement. Therefore, WFC can happen.

There is an uncertainty relation,

$$\Delta\phi \sim \frac{1}{\sqrt{\mathrm{N}_b}}, \tag{1}$$

where $\Delta\phi$ is the phase fluctuation of a macroscopic quantum state. A boson state follows this relation and becomes macroscopic for a large N_b.

C. Bosons composed of Cooper pairs of fermions

Exceptions to fermions are Cooper pairs in Bose-Einstein condensates. They are Cooper pairs of electrons in superconductors[9], those of Liquid He^3 in superfluids[10], and possibly those of neutrons in superfluids and those of protons in superconductors in neutron stars[11]. These Bose-Einstein condensates have superpositions of macroscopic quantum states, and therefore WFC can occur.

IV. Discussion

Previously, theories of quantum measurement have focused on explaining how SEVs become classical and have not covered an ensemble of measurements. The MIJ interpretation made the measurement problem simple and allowed the analysis of an ensemble of measurements.

For single-particle quantum mechanics, a MIJ or a single measurement does not produce a PD, and the wave function does not collapse. We have given some concrete examples.

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For many-particle quantum mechanics, we have only presented a framework and did not present concrete examples. However, thanks to the macroscopic nature of many-photon states and Bose-Einstein condensates, we can comment on their measurements as follows. Many-photon states are effectively classical electromagnetic waves, and they are amenable to ordinary measurements in a laboratory. A superconductor is also routinely measured in a laboratory, and in a sense, they are more easily measured than single quantum systems, which require amplification or accumulation. What we have found is an obvious fact that a measurement of a classical system gives a classical result. A quantum computer based on many-photon states or superconductivity may have an advantage in that the PD is obtained in principle from a single measurement.

Without confusion, we can introduce a new terminology, macroscopic quantum jump (MAJ), which is a QJ from macroscopic to macroscopic. In short, a MIJ is not a WFC, but a MAJ is a WFC,

V. Conclusion

We have shown that the final goal of quantum measurements is the determination of the probability distribution from an ensemble of system eigenvalues. If we define the collapse of the wave function to be the measurement of the probability distribution from a single measurement, the wave function does not collapse in single-particle quantum mechanics. In the case of many-particle quantum mechanics, the wave function collapses for many-photon states and Bose-Einstein condensates.

Statements and Declarations

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declarations

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