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Microscopic Quantum Jump: An Interpretation of Measurement Problem

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Abstract

Nearly a century has passed, since the birth of quantum mechanics, and yet the measurement problem has not been solved. We investigate the measurement problem from two aspects. First we scrutinize the basic postulates adopted by existing theories and identify the postulate of classicality of apparatus (PCA) to be the origin of the trouble. Second, we analyze the simplest possible experimental setup, a single photon particle as an observed system S and a detector as an apparatus A, and we find that a quantum jump occurs as a microscopic interaction between S and a single particle in A. We call this a microscopic quantum jump (MIJ). The MIJ selects system eigenvalues (SEVs) such as a two-dimensional position and arrival time for an incident photon. The MIJ outputs a microscopic particle (MIP), which carries the information of the SEVs potentially. In the apparatus A, the MIP triggers amplification cascade of secondary particles, which we call the intermediate particles (IMPs). The IMPs are initially a few, but become plenty after the amplification. The output of the amplification is a macroscopic observable (MAO) such as a current pulse, which carries the information of the SEVs in actuality. The measurement is complete when the MAO is obtained. By adopting the postulate of the MIJ and by discarding the PCA, we have constructed a measurement theory, which is consistent with standard quantum mechanics.

Keywords Quantum theory · Measurement problem · Foundations of quantum mechanics · Quantum jump

1 Introduction

In the history of science, quantum mechanics is the theory which has had the most profound impact on the way of thinking of human being. It also has succeeded spectacularly in the predictions of an enormous variety of phenomena (elementary particle physics, nuclear physics, atomic physics, molecular physics, solid state physics, and chemistry etc.).

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Although quantum mechanics requires drastic revision of classical physics, its mathematical and abstract formalism is firmly established. The principles of quantum mechanics are much more complex than those of classical physics and require a textbook like Dirac's [1] to describe them, though the book is completely self-contained.

Quantum mechanics is excellent in telling us about what we observe. However, if we start asking about what there exists, the situation becomes very complicated. This is the measurement problem in quantum mechanics. Following questions arise. What is the quantum origin of classicality? How does the transition from quantum to classical occur? What process is irreversible? Is the transition smooth or abrupt? These are the questions which have persisted from the birth of quantum mechanics. It has been nearly a century since quantum mechanics was established, and yet we cannot say that the measurement problem has been solved.

This paper is organized as follows. In Section 2, we introduce existing theories and scrutinize basic postulates adopted by them to elucidate perceived weaknesses of these theories. These weaknesses concern the postulate of classicality of apparatus (PCA) and postulate of superposition of macroscopic states. Our measurement theory is based on actual experimental setups. In Section 3, we present summaries of two kinds of detectors and their operating principles relevant to understand the essence of our measurement theory. There we postulate a microscopic quantum jump (MIJ). We will show that the apparatus is at least partly quantum mechanical and that the MIJ contradicts the PCA. The final goal of measurements is to obtain the probability distribution and a related type of detector is described in Section 4. Implications of our results are discussed in Section 5.

2 Existing Theories

Currently most theories of quantum measurements are broadly categorized into two classes, one class which assumes the central role of decoherence and the other which postulates the presence of a wave function collapse.

2.1 Decoherence Theory

At present the decoherence theory [2–5] appears to be the main stream to account for the quantum origin of classicality. The decoherence theory is based on the Hilbert space framework and Schrödinger dynamics.

In many occasions, effects of interference are suppressed in artificial or spontaneous manner. The decoherence theory is to investigate such occasions. This theory has been claimed to be directly related to the measurement problem in quantum mechanics, in particular to the emergence of classical world from quantum world. Environmental decoherence studies actual models of spontaneous interactions between an observed system and its environment which result in suppression of interference effects.

As a concrete example, let us consider a double slit experiment with electrons. The experimental setup is composed of a source of electron beam, a screen with two slits, and the second screen composed of a two-dimensional detector. In the normal situation, we will see an interference pattern at the last screen.

However, in some situations, this interference does not appear. This happens when some other systems interact with the electron between the slits and the detector. Those systems lead to entanglement with the components of the electron waves going through the two slits. This disappearance of interference is as if detections are made at the slits instead of the detector. For one electron, the patterns of detection with and without interference occur at the level of probability distribution. We cannot distinguish the probability distribution for entanglement with some other systems from that for using those systems for detection at the slits.

For instance, "some other systems" may be a lot of particles that wander around and scatter off the electron. The relative phase of the two wave components that pass through the two slits, is determined at the level of the composite system of the electron and stray particles. Except when a suitable experiment is performed for the composite system, interference is suppressed.

Environmental decoherence comes up through appropriate interaction between an observed system and its environment. Environmental interactions extinguish interference between states from some preferred set (eigenstates of decohereing variables). Intuitively, the observed system is monitored by the environment and this monitoring is effectively spontaneous and continuous measurement of some variable specified by the set of preferred states. In a sense, the environment can be regarded as a measuring device.

The eigenstates of the monitored observable are solid and are not disturbed by environmental interactions. The observed system becomes entangled with the environment. However, there are states that are least entangled with the environment and interference is suppressed between them. With regard to this, it is also said that effective superselection rules are induced by decoherence. This process is often called environment-induced superselection or einselection [3].

It has been claimed that the idea of decoherence can be applied to any system that contains very many degrees of freedom. In particular, it can be applied to a single quantum system in interaction with an apparatus without a further environment, because measurement devices possess enormously many degrees of freedom [2].

As to whether decoherence solves the measurement problem, the current status is summarized by Bacciagaluppi in the following manner [5].

Interference is very well suppressed between localized states of macroscopic objects. This seems to be directly related to why macroscopic objects appear to be in localized states. In the case of measurement devices, this fact would be relevant to why a device which is pointing to two different results is never observed. The question is whether we can model measurements with the environmental decoherence, so that the measurements always have results. As many physicists and philosophers have pointed out, the answer is negative [4, 6–8]. Why superpositions of measurement results are not observed is explained by decoherence. However, why measurement results are observed, is not explained in the first place.

2.2 Postulate of Classicality of Apparatus

In the decoherence theory and also in other existing theories, there is one implicit, but very basic postulate which we call the postulate of classicality of apparatus (PCA). Here we quote Omnès about this postulate [2].

"We understand clearly what an instrument is as long as we are describing it by classical physics and by common sense, but not otherwise. When an instrument is considered as a quantum object, it is tremendously complicated and it would then be unwise to say that we still understand it."

Due to this PCA, superposition of macroscopic states necessarily occurs and also a single quantum system interacts with enormously many degrees of freedom in the apparatus.

The postulate of the superposition of macroscopic states originates from the PCA. We will show later that in our experimental setup of an observed system S plus apparatus A, S interacts with only one particle in A at a time by a quantum jump and that this jump is from microscopic to microscopic. We call it a microscopic quantum jump (MIJ). The MIJ is a concept which contradicts the PCA by 100%. After the MIJ, there is no point in considering a Hilbert space or superposition of macroscopic states in the apparatus A. Additional difference of our theory from the decoherence theory is that in our experimental setup of S+A, there is no environment E.

2.3 Von Neumann's Theory

Our stand point postulates the presence of quantum jump, which is also called wave function collapse, wave packet reduction, reduction of superposition, or simply reduction. Here we summarize previously proposed theories based on the quantum jump.

We begin with von Neumann [9, 10]. In von Neumann's framework of the measurement process, he assumes two kinds of changes of quantum mechanical states. The first kind is the discontinuous, acausal and instantaneously acting measurements, which he calls arbitrary changes by measurements. The second kind is continuous and causal changes in the course of time, which evolve in accordance with the Schrödinger equation and he calls them automatic changes. An arbitrary change corresponds to a quantum jump. After analyzing the measurement process mathematically, von Neumann concludes that the repetition of automatic changes alone cannot complete a measurement and an arbitrary change is necessary at some stage. The question is where and how it happens. He claims that it is impossible to formulate a complete and consistent theory of quantum measurement without reference to human consciousness. From von Neumann's point of view, a quantum jump occurs somewhere in the human mind of the observer O.

In the same manner as the decoherence theory, von Neumann adopts the PCA and the postulate of the superposition of macroscopic states (actually he was first to do so). In von Neumann's theory, the presence of the observer O is essential. Without O, the measurement cannot be completed, while we consider that the measurement is completed in the apparatus A.

2.4 Copenhagen Interpretation

The second point of view regarding a quantum jump is the Copenhagen interpretation [2]. According to the Copenhagen interpretation, a measurement involves an action upon the measured object. It is often difficult to estimate how strong the action is and how deeply it perturbs the observed system. In any case, the action is assumed to cause a jump, which is certainly a consequence of quantum mechanics. However a jump is considered to be a new type of physical law according to Bohr. This jump is a random effect whose probability obeys the theory. However, its mechanism or its actuality is beyond the reach of the theory. The Copenhagen interpretation says that the quantum jump somehow exists, but does not say where or how.

We agree that the quantum jump is a random effect whose probability obeys the theory. We also agree that its mechanism of selecting eigenvalues of an observed system is beyond the reach of the theory. The quantum jump of the Copenhagen interpretation appears to be from microscopic to macroscopic, while our MIJ is from microscopic to microscopic. We are more specific about where and how the jump occurs as we will discuss later.

2.5 Jordan and Dirac

The third point of view regarding a quantum jump is of Jordan [11]. The essential point is that he treats a concrete observing setup as a thought experiment.

The experimental setup is shown in Fig. 1. Photons go through Polarizer 1 which produces linearly polarized photons. From this beam of photons, a single photon can be isolated, and this single photon hits Polarizer 2. We describe this process in the following manner. First a wave function of the single photon has to be generated. The wave function is a Maxwellian wave. This wave is divided by Polarizer 2 into two waves, Φ and Ψ. This division of the wave is the first step in the measurement process. We can use Polarizer 2 to let the photon make a *decision* — either to be reflected by Polarizer 2 or to go through it — and this is the *first step* of the measurement process.

We always apply a measurement device to split a given wave function into new wave functions $\phi_1, \phi_2, ...$, which are orthogonal to each other. These new wave functions are the eigenfunctions of the operator for the observable we try to measure. Virtually in every case, these different waves $\phi_1, \phi_2, ...$ must cover different portions of space. Then the planned observation is reduced to an observation of position. For example, the measurement of photon energy using a diffraction grating is reduced to the measurement of a photon diffracted to a particular angle.

However, Polarizer 2 does not complete the measurement and we should consider this point further. The interference between the two wave functions Φ and Ψ can still take place and this means that the *decision* has not yet happened. Therefore we let the wave Φ fall on a photographic plate (we assume an idealized photographic plate which detects a photon with 100% efficiency). Effectively, the decision is made by the photographic plate. There is no further interference between Φ and Ψ. Without contradiction, we can assert that now two distinct possibilities are left; absorption of one photon or none, with probabilities given by

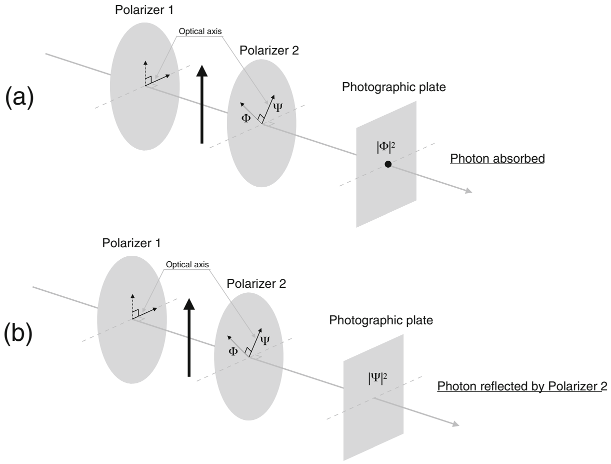

Fig. 1 Jordan's thought experiment. A single photon that goes through Polarizer 1 is linearly polarized in the vertical direction (optical axis of the polarizer is horizontal.). The wave function of the photon is split up by Polarizer 2 into two waves Φ and Ψ. Φ and Ψ are perpendicular and parallel to the optical axis of Polarizer 2 respectively. We let the wave Φ fall upon the photographic plate and this photographic plate makes the decision. There are two distinct possibilities; absorption of one photon (a) or none (b) with probabilities given by the intensities of Φ and Ψ

the intensities of Φ and Ψ. From Jordan's point of view, it is necessary for each observation to make — *by a real physical process* — the waves Φ, Ψ *incoherent* with each other.

A real physical process in the apparatus A, and not a mental act of the observer O, makes the decision. We will later elaborate Jordan's point of view in that the measurement is completed within the apparatus A and the presence of the observer O is insignificant. We will also show in Section 3 that a decision is made by a detector as by the idealized photographic plate considered by Jordan.

Dirac considers a similar thought experiment of polarization of photons to elucidate that what we all know is the probability of individual photon events and that what happens to a single event is beyond the reach of the theory [1]. In other words, the mechanism of a quantum jump is outside the domain of science, because it cannot be investigated by experiments. We agree with Dirac to the extent that the selection mechanism of eigenvalues of an observed system is outside that domain of science. Dirac appears to assume that this jump is from microscopic to macroscopic. We will show later that the jump is from microscopic to microscopic and that subsequent amplification is necessary to produce a macroscopic observable.

2.6 Collapse Theories

Finally, we mention the collapse theories [12–14]. The collapse theories merge von Neumann's two kinds of changes (arbitrary and automatic) in a unique description of dynamics. So the collapse theories modify quantum mechanics. The idea behind the collapse theories is that particles undergo spontaneous collapses of wave function which occur randomly in time and space. According to their formalism, a microsystem composed of a small number of particles takes a very long time to collapse, while a macrosystem composed of a large number of particles collapses instantaneously.

The collapse theories adopt the PCA and therefore the superposition of macroscopic states is assumed to exist. It has been claimed that the instantaneous collapse of macroscopic states, which occurs for a large system is the major success of the collapse theories.

Individual collapses in the collapse theories appear to be microscopic as our MIJ. However, what happens in the apparatus is totally different from our case. According to the collapse theories, in measuring devices, with their many degrees of freedom, the results of microscopic collapses become macroscopically significant because of the multiplication process. This multiplication is different from the amplification we will discuss later.

Since our MIJ is concerned with the interaction between S and only one particle in A at a time, it is different from the quantum jumps of the collapse theories, which are concerned with many degrees of freedom of the apparatus A. These many degrees of freedom again originate from the PCA.

3 Two Representative Experiments

In what follows, we consider the simplest possible experimental setup for a single photon detection and that for a single charged particle detection. These setups are composed of the observed system S (photon or particle) plus apparatus A (2D detector or 3D detector). There is no observer O or environment E.

The importance of these experiments is twofold. First, they are counterexamples for the PCA. Since the PCA is such a basic and general postulate, even the presence of one counterexample is significant. Second, detectors in general make *decision* if we use the terminology of Jordan (Section 2.5). Microscopic quantum jumps (MIJs) are physical processes related to decision. On the other hand, any physical processes that occur before the decision can interfere and are not MIJs.

3.1 Two-Dimensional Photon Counting Detector

We first consider a single photon detection by a two-dimensional photon counting detector composed of a photocathode with a micro-channel plate (MCP). A visible photon is the system S and the photocathode plus MCP is the apparatus A.

3.1.1 MIJ: Photoelectric Effect

Photo-sensitive portion of the photocathode can be regarded as a two-dimensional surface. We call the illuminated portion of the photocathode surface, a surface of potential contact. The probability distribution for the arrival of a photon on the surface of potential contact is given by quantum mechanics.

The photon hits one point on the surface of potential contact and gets absorbed and a photoelectron is emitted. This photoelectric effect is the MIJ. The system eigenvalues (SEVs) are the two-dimensional position and the arrival time of the photon. We call this position, the point of photon's arrival. The emitted photoelectron is a microscopic particle (MIP), which carries the information of the SEVs potentially.

We know the probability of where the photon arrives on the surface of potential contact, but we never know how the point of photon's arrival is selected. In other words, we do not know the mechanism of the MIJ before the point of photon's arrival is selected. This mechanism is outside the domain of science because it cannot be investigated by experiments [1]. However, we at least know the physics of the MIJ after the selection of the point of photon's arrival, which is the photoelectric effect.

3.1.2 Amplification: Electron Multiplication

The MCP is an array of capillary shaped electron multipliers for which high voltages are applied to cause avalanche of secondary electrons for a given trigger particle (Fig. 2). It is a

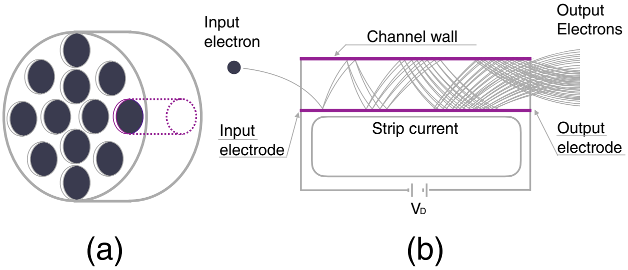

Fig. 2 Micro-channel plate (MCP). The MCP is an array of capillary shaped electron multipliers or micro-channels. The actual number of micro-channels is more than 10^6 and the figure (a) is oversimplified. The function of one micro-channel is shown in (b). Secondary electrons are amplified by several orders of magnitude

slab made from resistive material (often glass). It is about 1 mm thick with a regular array of tiny tubes or micro-channels leading from one surface to the other. The micro-channels are about 10 μm in diameter parallel to each other and enter the plate at a small angle to the surface (about 10° from the normal). The MCP functions as a particle amplifier, turning a single impinging particle into a cloud of electrons. By applying a strong electric field across the MCP, each micro-channel becomes a continuous dynode electron amplifier. A charged particle that enters one of the channels through a small orifice is guaranteed to hit the wall of the channel due to the angle between the channel and plate normal. The impact starts a cascade of electrons that propagates through the channel, amplifying the original signal by several orders of magnitude. The electrons exit the channel on the opposite side of the plate where they are collected on an anode, which is designed to allow spatially resolved collection.

The photoelectron as a MIP enters one of the electron multipliers and triggers amplification of secondary electrons, which we call intermediate particles (IMPs). The information of the SEVs is carried by the IMPs. The IMPs are a few and microscopic initially, but become plenty and macroscopic after the multiplication. The amplified IMPs result in a current pulse, which we call a macroscopic observable (MAO). The MAO carries the information of the SEVs actually. At this point the measurement of one photon is complete.

Since this amplification process occurs after the MIJ, it is outside the domain of standard quantum mechanics. The purpose of the amplification is to gain a sufficient pulse height to discriminate a true signal from unwanted low current pulses such as thermal noise. The absolute pulse height does not have a quantitative meaning. The relation between applied high voltage and the gain (secondary electron multiplication factor) is experimentally well known for a given micro-channel with given size, shape, and material. Practically this is sufficient. Modeling of electron multiplication was first made using a simple statistical theory based on classical electrodynamics, but the success of these analytical models was limited [15]. Later modeling based on classical electrodynamics using Monte Carlo simulations [16] was performed and it was able to reproduce observed data quantitatively. This method was found to be useful for designing a new device. So the modeling of amplification in a MCP is numerically complete.

A summary of individual stages is given in Table 1.

3.2 Three-Dimensional Detector of a Charged Particle

We consider the detection of ionization trail of a charged particle by a Wilson cloud chamber (WCC). WCCs are the most widely used charged particle detectors from 1920's to 1950's. A WCC is a glass chamber with a piston, containing air with water vapor (or alcohol). Then the piston is pulled outward to adiabatically expand the air inside the chamber, cooling the air and supersaturating the water vapor. The incident α particle is the system S and the WCC is the apparatus A, and this is a three-dimensional problem.

Table 1 Individual stages of photon detection by a photocathode plus MCP

MIJ	MIP	IMPs	MAO	SEVs
photoelectric effect	photo-electron	secondary electrons	current pulse	$(x, y; t)$

3.2.1 MIJ: Ionization of an Air Molecule

For standard temperature and pressure, the number density of air molecules is $n = 2.7 \times 10^{19}$ cm^{-3} and ionization cross section of a N_2 molecule (major constituent of air) by an α particle with a kinetic energy 10 MeV, is $\sigma = 3 \times 10^{-16}$ cm^2 [17]. Therefore the mean free path before one ionization occurs is $x = 1/(n\sigma) = 1.2 \times 10^{-4}$ cm. Since the ionization potential of a N_2 molecule (15.6 eV) is much smaller than 10 MeV, a series of ionizations occur. A volume of single contact is a cylindrical region defined by the cross section $\sigma = 3 \times 10^{-16}$ cm^2 and the mean free path $x = 1.2 \times 10^{-4}$ cm.

The reason why we estimated the volume of single contact is that the incident ionizing particle does not interact with arbitrarily many degrees of freedom at a time as expected from the PCA. Instead, the ionization process is a series of single ionizations, each of which is one measurement of a position. In fact, we can see a trail because the measurements are successive.

Ionization of an air molecule outputs an ion and an electron. Since the electron is driven away, the position of the ion keeps the information of the passage of the charged particle. Therefore the MIP is the ion for one measurement. One ionization is one MIJ and the three-dimensional position is the SEVs carried potentially by the MIP. We emphasize that the ionization process is not an interaction between the system S and arbitrarily many degrees of freedom in the apparatus A. Instead it is a series of measurements, each of which occurs in a volume of single contact.

3.2.2 Amplification: Condensation of Water Molecules

An ion of air molecule is microscopic and invisible as it is. Since water vapor is supersaturated, water molecules condense around the ion and a water droplet is formed. So the ion as a MIP is the trigger. This condensation is the amplification process and water molecules are the IMPs. The droplet is now a MAO, which carries the information of the position in actuality. This amplification or the condensation of water molecules is outside the domain of standard quantum mechanics, since it occurs after the MIJ or ionization in this case.

The growth of a droplet by condensation of water molecules around a molecular ion is a well known process. As in the case of absolute pulse height for a MCP, the absolute size of a droplet is not important as long as it is big enough. So the problem has been solved practically at least for our purpose of determining the position of a droplet. However, if we try to quantitatively model the growth of a droplet by a physical law, it becomes a formidable problem, which is still under study [18]. What is most difficult to model is the beginning of the growth of the droplet, a process called nucleation. The occurrence of atomic level events with length scale of 1Å, and the time scale of 10^{-13}s equivalent to the vibrational frequencies of atoms, makes the nucleation a very complicated phenomenon to study. Nucleation has not been solved as a quantitative problem. After nucleation, the growth of condensation is described by thermodynamics instead of quantum mechanics.

The track of the charged particle is obtained from a series of droplets and its initial energy can be obtained from the range using the Bethe formula [19]:

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4 n}{V^2 m}\left(\ln\frac{2V^2 m}{I(1-\beta^2)} - \beta^2\right), \quad (\mathrm{erg} \quad \mathrm{cm}^{-1}) \tag{1}$$

where n is the number density of the air molecules, V is the velocity of the particle, m is the mass of the particle and I is the mean ionization potential of the air molecule, in cgs units.

A summary of individual stages is given in Table 2.

Table 2 Individual stages of charged particle detection by a WCC

MIJ	MIP	IMPs	MAO	SEVs
ionization of air molecule	ion of air molecule	water vapor molecules	water droplet	particle trail & energy

3.3 What Standard Quantum Mechanics Tells us About

Standard quantum mechanics or single-particle quantum mechanics tells us about what happens stochastically when a MIJ occurs. Standard quantum mechanics tells us about the probability distribution on the surface of potential contact for a two-dimensional photon counting detection. It also tells us about the ionization cross section and a volume of single contact for a three-dimensional charged particle detection.

Standard quantum mechanics does not tell us about the mechanism of a MIJ, which is outside the domain of science [1]. We never know the point of photon's arrival on the surface of potential contact in the two-dimensional photon detection. We never know the impact parameter of a single collision of ionization in the experiment with the WCC, since the volume of single contact is just an average quantity.

Single-particle quantum mechanics covers up to the stage of the MIJ and it does not tell us about the mechanism of amplification. The amplification is outside the domain of single-particle quantum mechanics. Amplification does not even exist in the measurements with integration-type detectors as we will describe in Section 4.

Here we need to be more precise about the usage of the term "quantum mechanics" in relation to the amplification mechanism. In the case of a MCP in Section 3.1.2, amplification or electron multiplication is currently described by a numerical method based on classical electrodynamics. However, one can argue that quantum theory can describe the mechanism of electron multiplication. That description, if carried out numerically, would amount to perform multi-particle Schrödinger equation simulations involving a sophisticated modeling of the device components that participate at this amplification process. Certainly such simulations would be extremely challenging to carry out in practice, but they are not impossible as a matter of principle. While the amplification is outside the domain of single-particle quantum mechanics, it is not necessarily outside the domain of multi-particle quantum mechanics. At present there is no need for this sophistication by multi-particle quantum mechanics for two reasons. First the current numerical simulations are precise enough to derive the electron multiplication factor. Second, the output current pulse which tells us about the two-dimensional position and arrival time of an incident photon, only needs to be big enough. There is no quantitative importance in the absolute pulse height.

The PCA is a postulate generally adopted by most of the existing theories. Here we present some counterexamples for the PCA. These counterexamples are significant because the PCA is so general. It should be clear that the PCA is not applicable to these two representative experiments we described, because the interaction between the system S and the apparatus A is microscopic and quantum mechanical. The apparatuses we described are obviously quantum mechanical at least partly. It should also be clear that the superposition of macroscopic states does not exist because the amplification happens after the quantum jump.

We know the physical process of the MIJ after the selection of the SEVs. It is photoelectric effect in the case of the two-dimensional detector, and it is ionization of an air molecule in the case of the three-dimensional detector. So we are more specific about where and how a quantum jump occurs compared to other theories based on quantum jumps. So we have elaborated the point of view by Jordan and Dirac [1, 11], which is described in Section 2.5.

4 Final Goal of Quantum Measurements and an Integration-Type Detector

We have seen that amplification is outside the domain of standard quantum mechanics or single-particle quantum mechanics. In this section, we will show that only MIJs and statistics of MIPs are essential and that the amplification is of secondary importance or even it does not exist in some quantum measurements.

4.1 Final Goal of Quantum Measurements

Here we ask one question. Is the measurement of one set of SEVs useful by itself? Consider the Young's double-slit experiment. Is the location of one photon event meaningful? The experiment becomes meaningful after many photon events have been accumulated and the interference pattern is recovered. In other words, we need to measure the probability distribution to obtain amplitude and phase.

Another example is a scattering experiment in nuclear physics. Only one event does not tell anything about the scatterer, and we need to measure angular distribution of scattered particles to investigate the information on the scatterer such as the cross section. The angular distribution is again the probability distribution.

Our final goal of quantum measurements is to obtain probability distribution or expectation values of certain observables from a large number of individual events. What we need to do is to obtain statistics of MIPs, and in some detectors the statistics of MIPs are measured without the measurement of each event. They are integration-type detectors and below we describe one representative example of such detectors.

4.2 A CCD Image Sensor as an Integration-Type Detector

CCD stands for charge coupled device. A CCD image sensor directly obtains a probability distribution (or an image) without counting individual photon events.

A CCD is an array of numerous individual pixels each one of which absorbs photons and converts their energy to electrons within the semiconductor [20]. In order to make an imaging device, the electrons excited by the photons should not migrate away from the site of impact of the photons. For the purpose of confining the electron within a pixel, a special electric field to attract the electron to a specific spot, is required. In order to handle the arrival of multiple photons, there must be a storage. This storage can be made by applying metal electrodes to the semiconductor silicon together with a thin insulation layer made from silicon dioxide. The resulting structure is like a parallel plate capacitor capable of storing charge.

The voltage applied to the metal electrode generates an electric field inside the silicon slab. If the semiconductor is p-type, then a positive voltage on the gate will repel the holes which are in majority and sweep out a region depleted of charge just as in the pn junction. When a photon is absorbed, it produces an electron-hole pair, but the hole is driven out of the depletion region and the electron is attracted to the positive electrode. This capacitor can store the photoelectrons.

Consider the Young's double slit experiment using a CCD as the two-dimensional detector. The quantum efficiency is very high and we can assume that one photoelectron is excited by one incident photon. A MIJ occurs at pixel (x, y), which is the point of photon's arrival at time t and a photoelectron as a MIP is generated. Unlike photon-counting detectors, this MIP does not trigger amplification and carries the position information as the SEVs only potentially.

We need to integrate individual photoelectrons in time t to obtain a macroscopic number of MIPs. The measurement continues until the enough number of photoelectrons as MIPs are stored in each pixel or in other words until the accumulated MIPs at each pixel become macroscopic. The measurement is complete after resultant electron counts in individual pixels as MAOs are read out and then the interference pattern or the probability distribution is obtained. It should be emphasized that the SEVs of each MIJ are not observed. To reach the final goal of the measurements, the amplification that follows each MIJ is not essential. While MIJs are within standard quantum mechanics, the amplification is outside the domain of standard quantum mechanics as we have seen so far.

For faint source detection, a CCD is placed in an evacuated cryostat cooled to a cryogenic temperature and there environmental decoherence, which is a source of noise, is negligible. We call this type of detector an integration-type detector. Unless we measure time-critical observables, this type of detectors can always be used. We know how many photoelectrons are there in each pixel, in other words, we have the probability distribution obtained from a real ensemble.

5 Discussion

5.1 Old Questions

Let us consider the questions raised in the past concerning the measurement problem in the light of our microscopic quantum jump interpretation.

5.1.1 What is the Quantum Origin of Classicality?

We have seen that standard quantum mechanics covers up to the stage of the MIJ. Standard quantum mechanics is responsible for generating a MIP which carries the information of SEVs potentially. The MIP is a seed of classicality, but it is not classical by itself. The MIP triggers the next stage.

5.1.2 How Does the Transition from Quantum to Classical Occur?

The MIP triggers the transition. The transition occurs as amplification of secondary particles, but this amplification is outside the domain of standard quantum mechanics. In Section 3, we have described electron multiplication in a MCP and condensation of water molecules around an ion in a WCC as amplification mechanisms. We also describe the case of a microwave kinetic inductance detector in Appendix A, where the amplification is the process of energy downconversion. The amplification mechanism depends on the type of a detector. The result of the amplification is a MAO, which carries the information of the SEVs actually.

The amplification is not required for an integration-type detector for which the statistics of MIPs are directly obtained (Section 4). This fact also implies that the amplification is of secondary importance.

5.1.3 What Process is Irreversible?

We consider that there are two kinds of irreversibility. The first one is the MIJ. This process selects the SEVs, but we do not know its mechanism. However, it is obviously irreversible. The second one is the amplification. The essence of amplification is the cascade of secondary particles, and its reverse process does not exist.

5.1.4 Is the Transition Smooth or Abrupt?

We do not ask the mechanism of a MIJ, and in that sense, the MIJ is abrupt. The amplification is a chain of physical events, and in that sense, the amplification is smooth.

5.2 Back to Dirac

Jordan [11] and Dirac [1] are the two theorists who considered the relation between photon detection and a quantum jump. In this paper, we also studied photon detection and postulated the quantum jump. It appears that we inevitably must postulate the quantum jump in order to account for the photon detection. There may be a deep rooted reason, which we have not yet noticed. It may not be by chance that Jordan and Dirac are the two theorists who established second quantization [21].

Only difference between these two theorists and us is that we are more specific about the jump. We consider that the jump is from microscopic to microscopic. Except for this difference, we have come back to the textbook written by Dirac [1] in that we do not ask the mechanism of the quantum jump up to the stage of the selection of SEVs. However, this MIJ after the selection of the SEVs is a definite physical process such as photoelectric effect. The emission of photoelectron as a MIP is the result of the MIJ. We regard that standard quantum mechanics or the MIJ covers up to the stage of the emission of the MIP.

6 Conclusion

By adopting the postulate of MIJ and by discarding the PCA, we have constructed a measurement theory consistent with standard quantum mechanics. We hope that our theory is a meaningful step toward solving the measurement problem in quantum mechanics.

Appendix A: Most Modern Detector

The operating principles of a photocathode with a MCP and a WCC described in Section 3 are relatively simple. The outputs of amplification or MAOs are a current pulse and a water droplet respectively and the absolute pulse height and the absolute size of the droplet do not have quantitative meaning. The MAOs only need to be macroscopic. In Section 4, the operating principle of a CCD image sensor as a representative of integration-type detectors is described. In such detectors, the statistics of MIPs are directly obtained and there is no amplification of IMPs. So the operating principle is even simpler.

The necessary material to understand our theory has already been presented in the main text. However we have not covered all kinds of detectors. In this Appendix A, we describe a two-dimensional photon counting detector which is capable of measuring the energy of a single photon. Here we describe in detail a microwave kinetic inductance detector (MKID), which is one of the most modern and sensitive detectors at present. In this case, the absolute number of secondary particles produced by photon detection has a quantitative meaning. A MKID is important also in the sense that its operating principle is based on macroscopic quantum mechanics.

A.1 Microwave Kinetic Inductance Detector (MKID)

Now we discuss a photon counting detector with a capability of measuring the energy in addition to the two-dimensional position and time of arrival of an incident photon. A MKID [22, 23] is the most sophisticated two-dimensional photon counting detector operated from the infrared to UV wavelengths using superconductor. It is so sophisticated that the description of the operating principle becomes inevitably lengthy.

A.1.1 Function of a MKID

The photon detection part of the MKID is two-dimensional thin-film microwave resonant circuits, cooled to a cryogenic temperature T well below the super-normal transition temperature T_c. The metallic circuits (e.g. aluminum) are deposited on a substrate such as sapphire. Although the thin-film superconductor does not have resistance for d.c. current, it has finite impedance for a.c. current. The reason for this is as follows. The current in the superconductor is carried by pairs of electrons, or Cooper pairs, which are bound by electron-phonon interaction with a finite binding energy $2\Delta \approx 3.5k_BT_c$ (e.g. $T_c = 1.23$ K for aluminum). The Cooper pairs behave as bosons and condense in a superconducting state. If an electric field is applied near the surface of the superconductor, the Cooper pairs are accelerated and then kinetic energy is stored in them. Since the superconductor is non-dissipative, this kinetic energy can be taken out by reversing the electric field. In the same manner, magnetic field inside the superconductor, which penetrates a finite distance ($\lambda \approx 50$ nm) from the surface, can store energy. The net effect is that the superconductor has a surface impedance $L_s = \mu_0\lambda$ due to the reactive energy flow between the superconductor and the electromagnetic field. At a finite temperature T which is well below T_c, a small fraction of electrons are not in Cooper pairs due to the thermal excitation of quasiparticles (QPs). These electrons or QPs cause small a.c. resistance and the net impedance is $Z_s = R_s + i\omega L_s$, where ω is the angular frequency of the a.c. current and R_s is the resistance at ω. In this temperature regime, $R_s \ll \omega L_s$.

A number of resonant circuits with slightly different resonant frequencies are coupled to a through line, which transmits a comb of microwave probe signals at a range of frequencies generated by frequency synthesizers. Each resonant circuit corresponds to a pixel of a two-dimensional detector. At the end of the through line, resonances cause sharp dips of the transmitted signals. For each resonance, the amplitude and phase of a microwave probe signal are monitored. If a photon with sufficient energy ($h\nu \gg 2\Delta$) is absorbed by one of the resonant circuits (pixel), Cooper pairs are destroyed and QPs are created within the pixel. Due to the change of impedance induced by the photon absorption, the frequency of resonance is shifted by the change of inductance, and the depth of resonance becomes slightly shallower due to the slight increase of resistance. These changes are measured by those of the amplitude and phase.

Table 3 Individual stages of photon detection by a MKID

MIJ	MIP	IMPs	MAO	SEVs
destruction of a Cooper pair	photo-electron	quasiparticles & phonons	change of impedance	$(x, y, E; t)$

A.1.2 MIJ and Amplification

In the case of the MKID, detection of a visible photon is a complicated process [24, 25]. The photon hits one of the superconducting resonant circuits and it breaks a Cooper pair in that pixel. The total photon energy is effectively transferred to one of the two electrons in the Cooper pair and a high-energy photoelectron is excited. This process is a MIJ and the photoelectron is a MIP. The MIP carries the information of the total energy E as well as the position (x, y) and arrival time t potentially as SEVs. This photoelectron triggers downconversion of energy which involves interactions of QPs and phonons. These QPs and phonons are IMPs which carry the information of the SEVs potentially. Although the process of downconversion is complicated, it is fast and the final product is rather simple. First, this downconversion lasts only ns or less. Second, the downconversion results in an excess QPs whose energies are slightly greater than the gap energy Δ and phonons with subgap energies. The population of this excess QPs is $N_{qp} = \eta h\nu/\Delta$, where $\eta \approx 0.6$ is the fraction of the photon energy converted to the total energy of QPs. These QP excitations will last till two QPs encounter, emit a phonon, and recombine into a Cooper pair. This recombination time is order of μs to ms. The increase of QP density n_{qp} increases L_s and also increases R_s slightly. The fractional change in surface impedance is expected to be comparable to the fraction of Cooper pairs that are broken or

$$\frac{\delta Z_s}{Z_s} \approx \frac{\delta n_{qp}}{2N_0\Delta} \tag{A1}$$

where N_0 is the single spin density of states at the Fermi level. This way, the change of impedance is related to the photon energy through the number of excited QPs. This change of impedance carries the information of the SEVs actually and so it is a MAO. The energy downconversion or cascade is the amplification process in which the number of QPs becomes macroscopic. This occurs because the photon energy is much greater than the gap energy Δ of the superconductor. We emphasize again that the incident photon interacts with only one electron at a time as a MIJ and not with arbitrarily many degrees of freedom as the PCA predicts. A summary of individual stages is given in Table 3.

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References

1. Dirac, P.A.M. The Principles of Quantum Mechanics, 4th edn. Oxford University Press, Oxford (1958)
2. Omnès, R.: The Interpretation of Quantum Mechanics. Princeton Series of Physics. Princeton University Press, Princeton (1994)
3. Zurek, W.H.: Decoherence, einselection and the quantum origin of the classical. Rev. Mod. Phys. **75**, 715–775 (2003)
4. Joos, E., Zeh, H.-D., Kiefer, C., Giulini, D., Kupsch, J., Stamatescu, I.-O.: Decoherence and the Appearance of a Classical World in Quantum Theory. Springer, Berlin (2003)
5. Bacciagaluppi, G.: The Role of Decoherence in Quantum Mechanics. Metaphysics Research Lab. Stanford University (2020)
6. Pearle, P.: True collapse and false collapse. In: Feng, D.H., Hu, B.L. (eds.) Quantum Classical Correspondence: Proceedings of the 4th Drexel Sympsium on Quantum Nonintegrability, pp. 51–68. International Press, Cambridge, Mass (1997)
7. Bub, J.: Interpreting the Quantum World, 2nd corrected edition 1999 edn. Cambridge University Press, Cambridge (1997)
8. Adler, S.L.: Why decoherence has not solved the measurement problem: A response to P.W. Anderson. Stud. Hist. Philos. Modern Phys. **34B**, 135–142 (2003)
9. von Neumann, J.: Mathematical Foundations of Quantum Mechanics. Princeton University Press, Princeton (2018)
10. Jammer, M.: The Philosophy of Quantum Mechanics. Wiley, New York (1974)
11. Jordan, P.: On the process of measurement in quantum mechanics. Philos. Sci. **16**, 269–278 (1949)
12. Ghirardi, G.C., Rimini, A., Weber, T.: Unified dynamics for microscopic and macroscopic systems. Phys. Rev. D **34**, 470–491 (1986)
13. Ghirardi, G.C., Pearle, P., Rimini, A.: Markov process in Hilbert space and continuous spontaneous localization of systems of identical particles. Phys. Rev. A **42**, 78–89 (1990)
14. 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**, 471–527 (2013)
15. Adams, J., Manley, B.W.: The mechanism of channel channel electron multiplication. IEEE Trans. Nuc. Sci. **NS-13**, 88–99 (1966)
16. Guest, A.J.: A computer model of channel multiplier plate performance. Acta Electron. **14**, 79–97 (1971)
17. Bug, M.U., Garioni, E., Nettelbeck, H., Baek, W.Y., Hilgers, G., Rosenfeld, A.B., Rabus, H.: Ionization cross section data of nitrogen, methane, and propane for light ions and electrons and their suitability for use in track. Phys. Rev. **E88**, 043308–043321 (2013)
18. Karthica, S., Radhakrishnan, T.K., Kalaichelvi, P.: A review of classical and nonclassical nucleation theories. Cryst. Growth Des. **16**(11), 6663–6681 (2016)
19. Sigmund, P.: Particle Penetration and Radiation Effects. Springer Series in Solid State Sciences, vol. 151. Springer, Berlin (2006)
20. McLean, I.: Electronic Imaging in Astronomy. Wiley, Chichester (1997)
21. Tomonaga, S.: The Story of Spin. The University of Chicago Press, Chicago (1997)
22. Day, P.K., LeDuc, H.B., Mazin, B.A., Vayonakis, A., Zmidzinas, J.: A broadband superconducting detector suitable for use in large arrays. Nature **425**, 817–821 (2003)
23. Mazin, B.A., Bumble, B., Meeker, S.R., O'Brien, K., McHugh, S., Langman, E.: A superconducting focal plane array for ultraviolet, optical, and near-infrared astrophysics. Opt. Express **20**, 1503–1511 (2012)
24. Kozorezov, A.G., Volkov, A.F., Wigmore, J.K., Peacock, A., Poelaert, A., den Hartog, R.: Quasiparticle-phonon downconversion in nonequilibrium superconductors. Phys. Rev. B **61**, 11807–11819 (2000)
25. Kozorezov, A.G., Wigmore, J.K., Martin, D., Verhoeve, P., Peacock, A.: Electron energy down-conversion in thin superconducting films. Phys. Rev. B **75**, 094513–094524 (2007)