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The quantum measurement effect of interaction without interaction for an atomic beam

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ABSTRACT

When an atomic beam collectively and harmonically vibrates perpendicular to the wave vector of the beam, the number of atoms reaching the atomic detector will have a vibrant factor $\Delta t/T$ if the measurement time interval Δt is shorter than the period T. This new quantum mechanical measurement effect for an atomic beam is called interaction without interaction: though the translational motion of the atomic beam does not interact with its collective and transverse harmonic vibration, the latter will have an effect on the measured number of atoms associated with the former. From the new measurement effect the classical harmonic vibration's period is evaluated. We give a clear physical picture and a satisfactory physical interpretation for the measurement effect based on the Copenhagen interpretation of quantum mechanics. We present an experimental proposal to verify this measurement effect for an ion beam instead of an atomic beam.

Introduction

Measurement problem is an important problem in quantum mechanics. Although measurement is viewed in different ways among various interpretations of quantum mechanics, such as the Copenhagen interpretation [1], the many-worlds interpretation [2], de Broglie-Bohm theory [3], the many-minds interpretation [4], the consistent histories [5] etc, the different views of measurement almost universally agree on the practical question of what results form a routine quantum-physics laboratory measurement. The Copenhagen interpretation has been commonly used. In quantum mechanics a system is described by its quantum state, which contains the probabilities of possible measured physical quantities. Once a quantum system has been prepared in laboratory, some measurable quantities can be measured. The state of a system after measurement is assumed to collapse into an eigenstate of the operator corresponding to the measurement. Repeating the same measurement without any evolution of the quantum state will lead to the same result. If the preparations are repeated, the subsequent measurements will likely produce different results. The predicted values of the measurement are described by a probability distribution, or an expectation of the measurement operator based on the quantum state of the prepared system. The probability is either continuous (such as position and momentum) or discrete (such as spin), depending on the quantity being measured. The measurement process is often considered as random and indeterministic, but there are considerable disputes over this issue. A significant point in these disagreements is the collapse of the wavefunction associated with the state change in the following measurement. There are many philosophical issues, and the universal agreement is that we do not yet fully understand quantum reality. In any case, our descriptions of dynamics involve probabilities, not certainties.

Although the measurement problem in quantum mechanics has not been fully understood, several phenomena or paradoxes related to measurements have been proposed. These phenomena or paradoxes include Einstein-Podolsky-Rosen paradox [6], Schrödinger's cat [7], Wheeler's delayed choice experiment [8], quantum Zeno effect [9], weak measurement [10], Elitzur-Vaidman bomb tester [11] etc. When we study the problem of detecting an atomic beam, we find a new and interesting result. The atomic beam's collective transverse classical harmonic vibration will affect the mean number of atoms arriving at the detector. From the so-called vibrant factor the classical harmonic vibration's period is also evaluated [12,13]. The new quantum mechanical measurement effect is called interaction without interaction [14]. However, the interesting finding is only the calculated result and it lacks of a clear physical picture and a satisfactory physical interpretation, which belong to the contributions of this paper.

The paper is organized as follows: In Section "The Copenhagen interpretation of the new measurement effect of interaction without interaction" we give a clear physical picture and a satisfactory physical interpretation for the measurement effect of interaction

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without interaction based on the Copenhagen interpretation of quantum mechanics. In Section "An experimental proposal for verifying the measurement effect for an ion beam" We propose an experimental apparatus to verify this new measurement effect for an ion beam instead of an atomic beam. In Section "Summary ", we give a summary of this paper.

The Copenhagen interpretation of the new measurement effect of interaction without interaction

The new quantum mechanical measurement effect is called interaction without interaction, because the translational motions of the atomic beam does not interact with its collective and transverse harmonic vibration. When we measure the physical quantities associated with the translational motions, the collective and transverse harmonic vibration will have an effect on the measured physical quantities. Specifically, the measurement effect shows the influences of the collective classical harmonic vibration, whose vibrant direction is perpendicular to the wave vectors of the atomic beam, on the number of atoms measured by the atomic detector. One atomic beam in Fig. 1 has a collective classical harmonic vibration. The atomic beam is in the same wave surface, such that the atoms in the beam have the same phase. When the collective vibrant direction is perpendicular to the wave vector of the atomic beam, the vibration does not couple with the translational motions of the beam. Given the flux of the atomic beam j, the number of atoms in the beam is $N_0 = j \cdot \Delta t$ during a time interval Δt, i.e., the number of atoms measured by the atomic detector is N_0 if the atomic beam does not have a collective classical harmonic vibration. However, if the atomic beam collectively and harmonically vibrates with the period T, and the measurement time interval Δt is shorter than the period T, then the number of atoms measured by detector during a time Δt is given by [12,13]

$$< N >= N_0 \cdot \frac{\Delta t}{T} = j \cdot \Delta t \cdot \Delta t \cdot v, \quad (1)$$

where $v = 1/T$ is the frequency. The so-called vibrant factor $F \equiv < N > /(j \cdot \Delta t) = \Delta t/T$ is independent of the amplitude and the initial phase. This fact indicates that an atomic beam can be used to detect the classical harmonic vibrations with extremely micro amplitudes. The frequency of the classical harmonic vibration cannot be too high lest the measurement time interval Δt is too small and is difficult to be controlled in laboratory. From Eq. (1) the unknown frequency v or the period T may be evaluated.

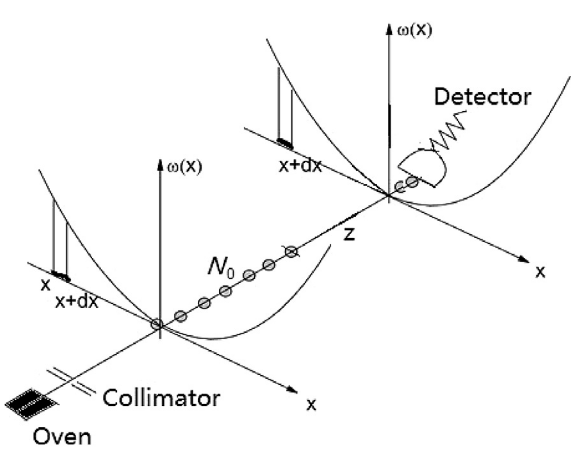

Fig. 1. The number of atoms measured by the detector will be less than the number of the incident atoms during a measurement time interval Δt shorter than the period T of the transverse harmonic vibration.

Eq. (1) looks very surprising. However, it is the exactly calculated result by quantum mechanics. How can we verify this result in the laboratory? First of all, one condition should be satisfied, i.e., the N_0 atoms flying along the z direction collectively vibrate with the same phase along the x direction both before and after they are registered by the detector, as shown in Fig. 1. This condition requires that the atomic detector be suspended and vibrate with the same phase, amplitude and period to those of the N_0 atoms.

There are two questions to be answered. Because the measurement time interval Δt is shorter than the period T of the harmonic vibration, the number of atoms measured by the detector $< N >$ is smaller than the number of the atoms incident on the detector $N_0 = j \cdot \Delta t$. Where do the atoms go? The detector vibrates harmonically with the same phase, amplitude and period to those of the N_0 atoms. The detector is static relative to the N_0 atoms, and the number of atoms arriving at the detector should be N_0 (we assume that the efficiency of the atomic detector is unity). Why does the vibrant factor $\Delta t/T$ appear during the measurement time interval Δt that is shorter than the period T?

All of the secrets hide in the detector! In the Copenhagen interpretation of quantum mechanics, the object always interacts with a classical laboratory device during a measurement. To a certain extent, the measurement of the object always produces an uncontrolled disturbance [1]. Neither the registered phenomena nor the classical laboratory devices keep the independent reality in the classical physics. Now there is not a definite boundary between the measured object and the classical laboratory device. Back to the problem of measuring an atomic beam, the detector harmonically vibrates with the same phase, amplitude and period to those of the atomic beam. The detector possesses the twofold functions: (1) registering the number of atoms arriving at the detector; (2) extracting the information of the measured object, specifically, the information of the classical harmonic vibration of the atomic beam. The atomic detector is not only a detector registering the number of atoms, but also a measured object, i.e., the classical harmonic vibration of the beam. Where do the atoms go? Why does the vibrant factor $\Delta t/T$ appear during the measurement time interval Δt that is shorter than the period T? Now everything is clear. The detector is static relative to the N_0 atoms, and therefore all the N_0 atoms arrive at the detector. During a measurement time interval Δt shorter than the period T, the detector also moves from the position x to the position $x + dx$, as shown in Fig. 1. The probability for the detector between x and $x + dx$ is exactly given by the vibrant factor $F = \Delta t/T$. It is the information extracted by the detector from the measured atomic beam that produces the vibrant factor. Finally the measured number of atoms is by coincidence equal to the incident N_0 atoms arriving at the detector multiplied by the probability of the detector, i.e. $\Delta t/T$, which coincides with the theoretical result Eq. (1) calculated by quantum mechanics.

An experimental proposal for verifying the measurement effect for an ion beam

Since an atomic beam is electroneutral, it is very difficult to be operated in the laboratory. If the atomic beam is replaced by an ion beam, the verification of the measurement effect becomes easy because an ion beam is charged and can be conveniently operated.

Fig. 2 shows how to verify the measurement effect for an ion beam. The ion beam from an ion source passes through a parallel-plate capacitor after it is collimated. The collective and transverse harmonic vibration of the ion beam can be produced by the alternating current (AC) electric field in a parallel-plate capacitor. In order to verify the effect, we require that the atomic detector harmonically vibrate with the same phase, amplitude

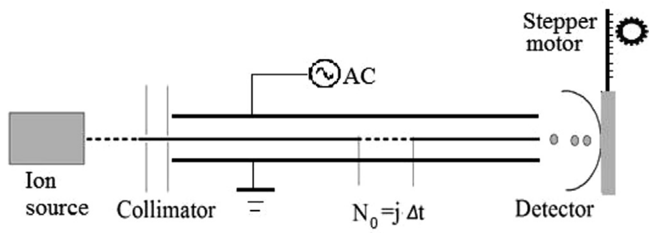

Fig. 2. An experimental apparatus to verify the new measurement effect for an ion beam.

and period to those of the N_0 ions. In the laboratory the atomic detector is driven by a stepper motor, we can ensure this condition by adopting the usual phase lock technique between the stepper motor acting on the atomic detector and the AC electric field acting on the parallel-plate capacitor. If the measurement time interval Δt is shorter than the period T of the harmonic vibration, the relationship between the measured number of ions $< N >$ and the incident number of ions N_0 should agree with Eq. (1). Then the measurement effect for an ion beam will quantitatively be verified.

Summary

In conclusion we give a clear physical picture and a satisfactory physical interpretation for our new quantum mechanical measurement effect of interaction without interaction for an atomic beam. From the vibrant factor we can evaluate the classical harmonic vibration's period. Surprisingly and interestingly, the new measurement effect for an atomic beam is actually a macroscopic quantum phenomenon, because the classical harmonic vibration and the process of the number of atoms registered by the atomic detector are both regarded as the macroscopic events. The new measurement effect of interaction without interaction for an atomic beam is not only interesting in quantum measurement theory, but also potentially important in applications. The so-called vibrant factor $F \equiv \Delta t/T$ is independent of the amplitude and the initial phase. This fact implies that an atomic beam can be used to detect the classical harmonic vibrations with extremely micro amplitudes and evaluate the period. We propose an experimental apparatus to verify this new measurement effect for an ion beam instead of an atomic beam. We hope that the experimental physicists pay attention to the new measurement effect of interaction without interaction for an atomic (ion) beam, and we believe that the new measurement effect will be verified with today's techniques.

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