A CONCEPTUAL EXPERIMENTAL VIOLATION OF TIME REVERSAL SYMMETRY

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The equations of quantum mechanics are time reversal symmetric. Here we use a simple conceptual double slit experiment to show that under certain circumstances time reversal symmetry is violated. We send a single particle from a source through a double slit to a detecting screen. Irrespective of how we reverse the momentum of the particle at the screen, we expect that it is unlikely to return to the original source. We interpret this to mean that when the position at which the particle arrives is probabilistically determined, time reversal symmetry is violated. Looking at the experiment in quantum mechanical term, we find the need to use a random unitary matrix in the equation giving the time evolution of the state of the system. This is due to a selection process that takes place during a measurement, wherein a system that can be in any of a number of states randomly ends up in only one of those states. This equation is not time reversal symmetric.

1. The Experiment

In the first phase we conduct a conceptual double slit experiment, as described, for example, by Feynman [1] and experimentally verified by Bach, et al [2]. Particles are emitted from a source on the left and travel towards a detecting screen on the right. In between the source and the detecting screen is a screen with two slits. The particles hitting the screen on the right are distributed in a series of peaks symmetrically distributed around a central peak. After determining the distribution of particles on the screen on the right we move onto the second phase of the experiment.

In the next phase we emit a single particle from the source and see where it arrives on the right hand screen. We then set up a collimated source at that location with the intention of imparting to it a momentum equal and opposite to that of the first particle. But we are faced with a dilemma. Because we do not know which hole the particle traveled through, we do not know the transverse value of the momentum and thus do not know in which direction to aim the source on the right. (See, for example, Feynman [1] on not knowing the transverse value of the momentum and how any attempt to measure the transverse value of the momentum, or equivalently determine which hole the particle passes through, would change the distribution of particles seen on the right hand screen.) The quandary we are faced with at this point can be taken as an indication that there may be a problem with conservation of time reversal symmetry. However, unwilling to abandon such a fundamental concept, we proceed with this phase of the experiment.

We might make the tentative assumption that were it not for our ignorance as to the state (transverse momentum) of the particle when it arrived at the screen on the right, we would have been able to aim the right hand source in the correct direction. For simplicity and without loss of generality we take the case where the first particle hits the right hand screen in the center of the distribution. We set up a detecting screen on the left and set the source on the right at all possible angles. For each angle we emit, say, one hundred particles and see where they land on the left. Due to interference, as illustrated in the first phase of the experiment, we expect to find that only rarely will a particle hit the left hand screen at the former position of the left hand source. In no case would we expect to find a set of conditions under which all one hundred particles arrive at the same position such as that of the source on the left.

We interpret the above results to mean that in this particular case time reversal symmetry is not conserved.

2. Random Variable

We consider the vertical position, y_i of a particle that is traveling from a source at x_l to a detecting screen at x_r, where l and r denote left and right, respectively. When a particle leaves the source on the left its vertical position is well defined; more exactly if we were to measure the vertical position of a series of particles just as they left the source we would find that the distribution was very narrow. This is in marked contrast to the distribution found for particles striking the screen on the right. There the distribution contains many widely distributed peaks. We conclude that the distribution has broadened significantly due to interference. (We ignore small changes in the transverse momentum, which complicates but does not change the thrust of the analysis.)

The change in position y_i of a single particle is

$$y_r = Ry_l. \qquad (1)$$

Before a particle is emitted from the source, the best we can do is assign to it a probability of attaining a specific final state y_r. The particular value for y_r is determined by experiment. A random variable is a function that assigns a number and an associated probability to each outcome of an experiment. From this vantage point *R* looks like a random variable and the two-slit experiment looks like a random process.

We consider the above in quantum mechanical terms in Sec. 4.

3. Hypothesis and Examples

We hypothesize that time reversal symmetry is violated whenever a system can evolve leading to several possible outcomes and where the outcome in a particular case is probabilistically determined.

In cases commonly labeled diffraction, such as electron and x-ray diffraction, particles are emitted from a source of relatively small dimensions and their distribution at the detecting medium is significantly broader. Any attempt to send a particle on a return journey towards the source will usually result in the particle failing to reach the original source. In these cases time reversal symmetry is violated.

4. Quantum Mechanical Description and Effect of Measurement

Above we have described the outcome of our conceptual experiment in terms of expected physically observable results. We now desire to describe the same phenomenon in quantum mechanical terms. In place of observables we use the quantum state $\left|\Psi(t)\right\rangle$ and look as how it changes when a particles goes from the source on the left to the detecting screen on the right.

We represent the state of the particle when it leaves the source by $\left|\Psi_l\right\rangle$. Diffraction causes this state to split into a continuous spectrum of states. We represent a single one of those states just before the particle hits the detecting screen by $\left|\psi_{r-\delta}(y)\right\rangle$, where y is the transverse position and δ is an infinitesimal. By the principal of superposition we obtain for the state of the system

$$\left|\Psi_{r-\delta}\right\rangle = \int c(y)\left|\psi_{r-\delta}(y)\right\rangle dy \;, \tag{2}$$

where

$$p(y) = c(y)^* c(y) \tag{3}$$

is the probability distribution obtained in the Phase 1 experiment described in Sec. 1. We can also write the change in state as

$$\left|\Psi_{r-\delta}\right\rangle = {}^{D}U\left|\Psi_l\right\rangle, \tag{4}$$

where ${}^{D}U$ is a unitary transformation, and the superscript denotes diffraction.

The position at which the particle hits the screen is randomly determined. Its wave function is given by

$$\left|\Psi_r\right\rangle = {}^{M}U\left|\Psi_{r-\delta}\right\rangle, \tag{5}$$

where ${}^{M}U$ is a random matrix and the superscript denotes measurement. Combining Eqs. (4) and (5) gives the change in state for the overall process as

$$\left|\Psi_r\right\rangle = {}^{R}U\left|\Psi_l\right\rangle \tag{6}$$

where ${}^{R}U$ is a random matrix given by

$${}^{R}U = {}^{M}U\,{}^{D}U \,. \tag{7}$$

Eq. (6) is not time reversal symmetric. When time reversal symmetry holds

$$\left|\Psi_l\right\rangle^* = {}^{R}U^{\dagger}\left|\Psi_r\right\rangle^* . \tag{8}$$

But because ${}^{R}U^{\dagger}$ is a random matrix

$$\left|\Psi_l\right\rangle^* \text{ Eq. (6)} \neq \left|\Psi_l\right\rangle^* \text{ Eq. (8)}, \tag{9}$$

and time reversal symmetry does not hold.

Here the failure of time reversal symmetry is due to two successive events. First due to diffraction the state of the system splits into a multiplicity of states. Then a selection process, brought on by the particle interacting with the screen on the right, randomly picks one of those states. That selection process is commonly called making a measurement, however there is no requirement that a measurement be made or that the screen even be capable of making a measurement.

5. Summary and Discussion

We examined time reversal symmetry in the context of the two slit experiment. First we looked at the expected outcome of a connectional experiment in which we sent a particle from a source through a screen containing two slits and then onto a detecting screen. We found that if we tried to send a particle from the detecting screen back to the source that we would usually fail. Our interpretation was that ime reversal symmetry did not hold.

Looking at this using quantum theory we found that the random selection of the position at which a single particle hits the screen introduces the need to include a random unitary matrix into he equations of motion. A consequence of this is that time reversal symmetry does not hold.

The physical ideas used in developing these results are well accepted. It is the interpretation of the experiment in Sec. 1 and the assertion that one need include a random unitary matrix in the quantum mechanical equations of motion that are unique.

When using the usual equations giving the time evolution of a quantum system, such as

$$\left|\Psi(t)\right\rangle = \exp[(-i(t-t_0)H/\hbar]\left|\Psi(t_0)\right\rangle, \qquad (10)$$

the state of the system $\left|\Psi(t)\right\rangle$ is uniquely determined over time [1]. The inclusion of the random effect of "measurement" in the equation of motion, as in Eq. (6), means that even at the quantum level the time evolution of the state of the system is not deterministic.

The above results are relevant to resolving the conceptual difficulties in placing the field of statistical mechanics on a firm quantum mechanical foundation. The conceptual difficulty in statistical mechanics arises because the classical equations of quantum mechanics are time reversal symmetric and if they govern the time evolution of a non-equilibrium isolated system, the state of the system cannot evolve towards equilibrium over time [3]. This is contrary to what is observed.

We assume that the above results can be extended to systems where scattering occurs in a sequential series of events, as in isolated thermodynamic systems. Broadly we expect the following: when two particles interact they are scattered and assume a multiplicity of states. When one of those particles subsequently interacts, it randomly assumes one of those possible states. This process repeats itself, permitting the state of the system to evolve. Because of randomness, the process is not time reversal symmetric.

The fact that non-equilibrium isolated thermodynamic systems evolve and stochastic methods [4] have been successfully used to describe the behavior of these systems is an indication that time reversal symmetry is not observed.

We show in another paper [5] how a particular form of the random unitary operator leads to the master equation.

References

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