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Quantum Mechanics and the Arrow of Time

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Quantum Mechanics and the Arrow of Time

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Abstract

We show time reversal asymmetry in quantum mechanics by isolating a single, solitary hydrogen atom in a black body, deriving from it the diagonalized Hamiltonian matrix in continuous time, and using it to visualize the irreversibility of the emission and absorption of radiation. Graphic evidence in support of the model is obtained from experiments performed with the simplest quantum system, an electron cyclotron. The experimental evidence is used to obtain equations of motion to describe time asymmetry with respect to the energy-time conjugate variables in linear time which complement the time symmetric equations of motion in position-momentum coordinates given with respect to cyclical time. Theoretical arguments by Feynman and Einstein are shown to support time reversal asymmetry.

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1. Introduction

Microscopic time reversal refers to the fact that the fundamental laws governing individual particles (like electrons and atoms) are symmetric with respect to time, meaning they work the same forwards or backward. The Schrödinger equation possesses time-reversal symmetry because its fundamental dynamics allow for wave function evolution both forward and backward in time. If time is reversed (t—> −t) the equation still holds and results in another valid solution. Consequently a video of a quantum process, if played backward, would look like a physically valid phenomenon.

In statistical mechanics microscopic reversibility means that in general for every tiny process, a reverse process is possible, and it leads to the idea that statistical theories like the detailed balance equation are able to maintain equilibrium as a result. Despite the appearances of reversibility at the microscopic level, macroscopic irreversibility holds in large systems due to increasing entropy and the second law of thermodynamics

2. Quantum Mechanics

2.1. Time's Arrow

We see evidence of the arrow of time in the second law of thermodynamics, in evolutionary theory, in Hubble's law of cosmic expansion; and also subjectively, in our own stream of consciousness. All are irreversible natural phenomena that may well be based on underlying quantum mechanical principles. They are well-known examples of time's arrow that are observable. However, time is not an observable in quantum mechanics. Observables are measured by bringing a measuring device into contact with the physical system, but time measurements do not make contact with the observed physical system. The time "measured" by clocks is just one of four coordinates, the same as in classical physics, and though clocks are used in quantum mechanics to measure the location of an event, the time of an event has no direction. Thus time asymmetry is concerned with much more than clock time and the time we experience. It is also a determining factor in how material systems evolve in time; whether in the form of a hydrogen atom, a molecule, the cosmos, or life itself.

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2.2. Two Formulations of Time

In 1925 Heisenberg formulated his theory of matrix mechanics based on "quantum jumps" at single points in time. The following year Schrödinger introduced wave mechanics that is based on the wave function evolving cyclically in time. Thus a conflict has always existed between these two foundational, mathematically equivalent formulations of quantum mechanics concerning how quantum systems evolve in time; discretely or continuously. The first record of the dispute, which included Bohr, was conducted verbally and with great vigor and intensity [1]. We will now renew the debate a century later with an improved understanding of the foundations and access to experiments that directly illustrate the topic of the discussions; that is, how the excitation and decay of an electron evolves in time.

2.3. Time Reversal Asymmetry

Wave functions determine the nature of physical variables in quantum mechanics and they evolve according to the Schrödinger equation reversibly in time. However, there is a mathematically equivalent theory, matrix mechanics, which describes physical variables at single points in time. It derives from the hydrogen spectrum of black body radiation and is the result of many atoms acting in unison. We are able to use it to interpret the energy of a single hydrogen atom by reformulating the Hamiltonian matrix H_{ij} describing all possible electron transitions [2]. The individual matrices H_{ij} are snapshots in time of energy states that are infinite in number, and when placed in a series from low energy to high they may be used in the same way as frames in a motion picture to depict the increase in temperature of a hydrogen atom. The same video shown in reverse is immediately rejected since it depicts the spectral lines being generated in response to a lowering of temperature. Therefore a reformulation of matrix mechanics in continuous time with respect to a solitary hydrogen atom forms the basis for a hypothesis concerning the arrow of time at the most fundamental level possible, the quantization of energy.

3. Experimental Evidence

3.1. The Quantum Cyclotron

A recent experiment with single electrons provides experimental evidence to support our hypothesis concerning quantum mechanical asymmetries in time [3]. Electrons from a high voltage discharge tube are cooled to near absolute zero and inserted in a "bottle" made of intersecting electric and magnetic fields. Single particles are trapped indefinitely by the intersection of a homogeneous magnetic field and an electrostatic quadrupole potential. The resultant motion of electrons consists of a fast circular cyclotron motion with a small radius superimposed on a much larger orbit moving slowly. The trapped electrons constitute an artificial atom or "quantum cyclotron", the simplest quantum mechanical system possible. It is so sensitive to external forces that the influence of the earth's gravitational field must be taken into account.

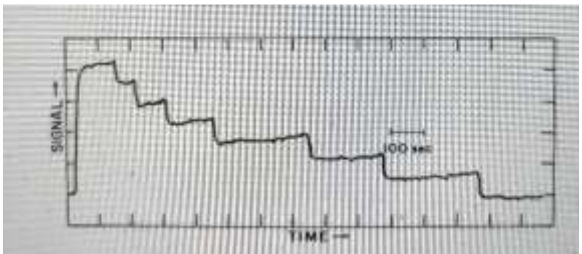

FIG. 5. Steps in the detected axial signal that appear when the axial drive is increased sufficiently to drive one electron at a time out of the trap. It is evident that there were initially seven electrons in the trap. The initial and final signal level is the noise floor (Wineland, Ekstrom, and Dehmelt, 1973).

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Energy levels of a quantum cyclotron

When a signal of alternating frequency is applied to the axial cyclotron motion it causes the electrons to be excited and seek a higher energy level. The "detected current" plotted as a function of energy versus time in the figure shows a pronounced step structure with quantization slowed to a snail's pace. Initially there are seven electrons in the cavity, each one described by a wavefunction and probability for decay. Emission proceeds spontaneously in discrete steps of equal energy with each one marking the exit of an electron from the cavity. The system returns to the base level when the final electron exits. The figure gives a complete record of quantization in terms of the physical variables energy and time; beginning at a base level, or ground state, and also ending there. The horizontal lines represent the presence of wave functions, the short vertical lines represent emissions, and the long vertical line at the left represents the input signal. None of the vertical lines are reversible since they cannot be recreated if time is reversed (t—> −t).

The curve is a complete description of quantization since it includes the absorption of energy in the form of a continuous classical signal and the discrete emission of energy. It complies with the conservation of energy by beginning and ending at the same base level, but the wave function is a partial record of quantization because it does not begin and end at the same energy level. A wave function collapses each time an emission occurs but in this simplest of all quantum phenomena collapse and entanglement are irrelevant. The curve suggests that the classical and quantum properties of matter are irretrievably linked in black body radiation for one cannot exist without the other.

In this section we note that time's arrow in quantum mechanics is observed to be asymmetric when classical absorption is taken into account. In the next section we will see that the same thing happens in statistical mechanics when quantum properties are taken into account.

3.2. Statistical Mechanics

Individual particle collisions and forces obey time-symmetric laws, meaning they could happen backward and still be physically valid. Statistical mechanics shows that while fundamental particle interactions are time-reversible, macroscopic systems appear irreversible due to overwhelming probability, meaning systems naturally move from ordered (low entropy) to disordered (high entropy) states because there are vastly more disordered arrangements possible. This makes a spontaneous return to a specific ordered state incredibly unlikely, though theoretically possible over immense timescales (Poincaré recurrence). The theory that the "arrow of time" is a statistical phenomenon, not a violation of underlying reversible laws, cannot be refuted mathematically. It is claimed that the underlying rationale is only wrong if the equations are wrong.

The time symmetric laws of statistical mechanics are based on the assumption that atoms and molecules may be treated as points. However Nobel laureate Richard Feynman noted that there are difficulties involved in treating even the simplest of atoms, hydrogen, as a point [4].

> "But suppose we look at the whole hydrogen atom as a "particle." If we didn't know that the hydrogen atom was made out of a proton and an electron, we might have started out and said: "Oh, I know what the base states are—they correspond to a particular momentum of the hydrogen atom." No, because the hydrogen atom has internal parts. It may, therefore, have various states of different internal energy, and describing the real nature requires more detail."

Atoms collide inelastically, with some energy being absorbed internally and some being exchanged due to momentum according to Newton's laws. To determine whether the equations are time symmetric or asymmetric both must be considered. Einstein differentiated very clearly between the internal and external dynamics of the molecule. The molecules follow the reversible equations of classical mechanics in laboratory coordinates and the electrons follow the equations of quantum mechanics with respect to atomic or molecular coordinates [5].

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> "For the time being, we disregard the radiation emitted and absorbed by the resonators and look for the condition for dynamic equilibrium corresponding to the interaction (collisions) of molecules and electrons. For such an equilibrium, the kinetic theory of gases provides the condition that the mean kinetic energy of a resonator electron must be equal to the mean kinetic energy of the progressive motion of a gas molecule."

Quantum laws are involved in the atomic and molecular collisions that determine "the mean kinetic energy of a resonator electron", so in order for detailed balance to exist statistical mechanics must be asymmetric in time.

4. Conclusion

The experimentally derived energy-time curve in the figure is a faithful reproduction of quantization in real time; the continuous, irreversible increase and decrease of energy by a quantum system. We are able to visualize quantization in the figure by picturing how the electron moves as the radius of axial cyclotron motion increases due to the input of a signal, and then decreases when energy is released. The experiment reduces the complexity of quantization to its most elemental level, the increase and decrease of a potential, yet it is compatible with the more complex probability distributions predicted by the wave function in position-momentum coordinates for they refer to two different types of time, linear time and cyclic time. Because there are pronounced discontinuities in the slopes of the curve it cannot be reproduced by a single equation. The correct equations, derived with respect to the conjugate variables energy and time, appear in a previous communication [1].

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