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Quantum Mechanics and the Arrow of Time

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Abstract

Matrix mechanics is not considered important for understanding quantum mechanics; however, it is the key to understanding time reversal asymmetry. We use a single, solitary atom to derive the diagonalized Hamiltonian matrix in continuous time and use it to visualize the irreversibility of time in a quantum system. Graphic evidence in support of the model is obtained from experiments performed with the simplest quantum system, an electron cyclotron. Theoretical arguments supporting time asymmetry in statistical mechanics that were presented by Feynman and Einstein are also cited. It is hypothesized that equations describing time reversal asymmetry must be derived in energy-time coordinates.

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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.

2.0. Quantum Mechanics

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 natural phenomena that may well have quantum mechanical principles underlying them. 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 physical variables evolve in material systems; whether in a hydrogen atom, a molecule, or the cosmos.

Wave functions determine the nature of physical variables in quantum mechanics and they evolve according to the Schrödinger equation which is reversible 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

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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 [1]. 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 the release of energy and 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.

2.1. Experimental Evidence

A recent experiment with single electrons provides experimental evidence to support our hypothesis concerning quantum mechanical asymmetries in time [2]. 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 slow circular drift motion in a large orbit carrying with it a fast circular cyclotron motion with a small radius. 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.

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 signal 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 final level marks the return to the base level. 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 which are reversible, but the vertical line at the left represents the input signal that is not reversible since it cannot be recreated if time is reversed ($t \longrightarrow -t$). The curve, which is a complete description of quantization because it includes the classical signal and discrete emissions, is asymmetric in time. Quantization complies with the conservation of energy by beginning and ending at the same base level, but the wave function does not comply because it is a partial record of quantization and does not begin and end at the same energy level. The curve suggests that the classical and quantum properties of matter are irretrievably linked in quantum systems for one cannot exist without the other.

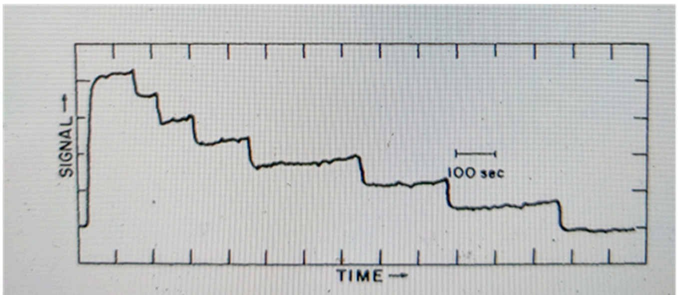

FIG. 5. Steps in the detected axial signal that appear when the axial drive is increased sufficiently to drive one electron at a time out of the trap. It is evident that there were initially seven electrons in the trap. The initial and final signal level is the noise floor (Wineland, Ekstrom, and Dehmelt,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

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Figure 1. Energy levels of a quantum cyclotron.

In this section we noted that time's arrow in quantum mechanics appears symmetric when classical absorption is ignored. In the next section we will see that the same thing happens in statistical mechanics when quantum properties are ignored.

3. 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 [3].

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 equations of classical mechanics in laboratory coordinates and the electrons follow the equations of quantum mechanics with respect to atomic or molecular coordinates [4].

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 atomic and molecular collisions except at temperatures near absolute zero so in the case *real* gases statistical mechanics is asymmetric in time.

4. Conclusions

The experimentally derived energy-time curve in the figure is a faithful reproduction of a complete quantization process, the irreversible increase and decrease of the energy of a quantum system. We can use it to visualize quantization because it reduces the complexity of atomic structure to its most elemental level yet it is consistent with predictions made by non-relativistic formulations deriving from the emission and absorption of radiation. Because the slopes of the curve are nearly vertical or nearly horizontal 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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