ISSN No:-2456-2165

Time Crystals: A New State of Matter; Chaos Complexity and Order in the Time Dimension

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Abstract:- The concept of time crystals originated with the seminal idea of Frank Wilzek, in 2012. The first time crystal was claimed to have been created in 2016, trapping ions in Ytterbium atoms at the University of Maryland and the second in the same year in diamond, at Harvard University .In 2021, a team of Google scientists created a time crystal in its Sycamore Processor.
This paper aims to project the creation of time crystals as a process that involves the appearance of Chaos causing bifurcation and resulting in Complexity and order with a cyclic attractor in the time dimension. Anderson Localization and Many Body Localization produce the Complexity and resultant order that is analogous to similar order in the space dimension, in a nonlinear equilibrium ambience. Furthermore, Many Body Localization involves interaction of states where time translational symmetry is broken, with the interplay from Chaos to order. This occurs within the framework of Condensed Matter Physics, as a stabilizing mechanism leading to Complexity and order.

I. INTRODUCTION

Time crystals are a new phase of matter where they travel in a repeating and regular cycle without using any energy.[1]

Normal crystals have atoms arranged in a repetitive pattern in space. Since we live in a world where we conceive three dimensions of space and one of Time, physicists have pondered whether the atoms of a crystal could be arranged in a repeating pattern in time, as they are in space.

To create a time crystal, let us suppose we create a crystal in one state. If we now blast the same crystal with a laser, which is finely tuned, the atoms in a crystal flip into another state -flip back again, and continue to do so without consuming any energy .Thus we have created matter which is perpetually in motion, without absorbing any energy.

The idea is sometimes said to contradict two of the major laws of Physics, that of conservation of energy and the other of the Second Law of Thermodynamics.

II. BROKEN SYMMETRY

Time crystals are capable of breaking symmetry, similar to space-translation breaking symmetry [2].On the surface of a crystal , freezing molecules of a liquid in contact can align such that a less symmetric pattern develops. Thus symmetry is broken.

The idea that time symmetry could be broken in the lowest energy level of a quantum system in the mechanical domain was first proposed by Nobel Laureate Frank Wilzek in 2012 in his historic article on time crystals.

When time symmetry is broken, the time crystals would reach a stable state, which is also the lowest energy state, without consuming any energy[3] .The movement of the atoms and the crystal would be set in perpetual motion.

The ground state is defined as the zero energy state. When the state is dependent on time, there is a change in some quantity, that is, energy, which implies movement.

The idea of perpetual motion without expending energy sounds absurd, and diverges from fundamental laws of Physics.

There are different properties of space crystals which are also useful. Crystals In space can behave as superconductors, conductors or insulators. Infact, all condensed matter properties prevalent in the space dimension can, in future, be analysed in the time dimension.

III. MANUFACTURING TIME CRYSTALS : ONSET OF CHAOS AND COMPLEXITY WITH ORDER IN THE TIME DOMAIN

The first Time Crystal was claimed to have been built in October 2016 by a team from the University of Maryland headed by Christopher Monroe. The procedure involved trapping a group of Ytterbium ions in a trap known as Pauli Trap which confines the ions using electromagnetic fields under radio frequency. A pair of laser beams targeted two spin states. The beams were pulsed, the pulse shapes being controlled by a modulator of the acousto-optic type, also using a Tukey window for avoiding excess energy appearing at different optical frequencies. Oscillations below the harmonic were observed. The Time Crystal assumed an unchanging frequency of oscillation which remained undisturbed and developed a vibrating frequency of its own even when perturbed. Thus It had assumed Complexity and subsequent order under Chaotic conditions. The crystal, however, lost its oscillation when the perturbation frequency became too strong and moved back to the same state as before with the induced frequency.

In the same year (2016), a group at Harvard headed by Michael Lukin reported the creation of a Time Crystal in diamond [5]. The group doped a diamond crystal with highly contracted centers having nitrogen vacancy. Such doped crystals possess strong dipole to dipole coupling where the

ISSN No:-2456-2165

dipole spin interacts .The system was subject to driving microwave fields and an optical laser field to determine the spin state. At about half the frequency of the microwave drive, spin polarization evolved, and the oscillations continued for 100 cycles. Such observations indicate order in the Time Crystal domain. Again, the spin derived oscillation indicated an onset of Chaos, leading to Complexity and order.

In July 2021, a team of Google scientists and Physicists from many universities observed the creation of a Time Crystal on Google's Sycamore processor [4]. Many Body Localization was achieved using a 20 qubit chip that resulted in up and down spins. Stimulation was carried out using a laser to achieve a Floquet system (a system where particle spins flip up and down in cycles which are periodic). The system absorbed no energy and remained in an eigenstate order, again developing the onset of Complexity from Chaos.

A. Anderson Localization in the Time Dimension

In a space crystal, if the disorder is sufficiently strong, the electrons cannot contribute to an electric current because of destructive interference from scattered paths and instead become localized as predicted by the Nobel Laureate Philip Anderson in 1958. The Anderson Localization can occur in the time dimension where disorder in space is replaced by disorder in time [6].

This also signifies that Chaos can occur in the time dimension in Non equilibrium systems, leading to time crystals [7], flipping between two states. Without consuming energy and obtaining Complexity and balance of order.

The detection probability or $|\Psi(t)|^2$ can be Anderson localized . In the time dimension, it is somewhat easier to introduce controlled disorder, simply by the application of some disorder to the system by a fluctuating force.

B. Localization , Many Body Localization , Ordered Complexity in Time Crystals from Chaotic disorder

Localization of a particle implies that its wave function will not spread over time, and stays in its initial position. Philip Anderson theorized in 1950 that disorder is able to localize a particle disregarding quantum tunneling and other phenomena that may cause movement. When disorder increases (and Chaos and bifurcation dominates), particles are non localized and consequently follow a transition state (Anderson state of transition) where they can then localize. This follows in Electrical and Electronic circuits in the metallic state, when electrons move as current. The ordered state of Localization occurs in a domain of Complexity, which the waves attain after Chaos. The disorder normally arises from a random changing potential such as a magnetic field, reactions that occur in the system in disorder, or an external form , as a laser pulse in producing time crystals.

In classical systems, as in local wires, localization is not desired since the electrons must move.

In the Quantum realm, we can analyze the disorder as a destructive interference in the wave. However, when the wave is traveling from one point to another and back again to the same point, it may meet another wave coming from the opposite direction, and causing constructive interference. Thus the wave function gets boosted many times at the same initial location and is likely to be partitioned. Localization is a general concept that can apply to any characteristic of a particle, including spin[8] . The importance of spin arises as it can frequently be used to store information, especially in quantum computers. Spin, after interaction with fields, can propagate similar to location. Random Fluctuations in spin coupling is the result of Chaotic disorder, and order sets in with localization, in the time domain, just as it does in the spatial domain. with transition between two states, having a cycle attractor.

C. Many Body Localization (MBL) , Complexity and Order

When there are a large number of particles that are interacting, each of the particles can be localized and constitute what is known as Many Body Localization [8]. Because of interference, the atoms subject to high disorder attain a state of spin and energy where movement is restricted. This leads to Many Body Localization and continuity of the initial state.

Such a system does not run down as it is unable to move away from the initial state.

Localization attains Complexity in the system, and is the first step towards the creation of a Time Crystal, which is a stable state within the non-equilibrium ambience. As observed, the Google Time Crystal is a Floquet system. With the use of a Floquet circuit, scientists have been able to cycle the qubits (representations of spins up or down) between states (1 and 0, for example) over time. This is the second and final step towards the creation of a Time Crystal. The 20 superconducting cubits used by Google constitute a cycle, producing long range order from Complexity using quantum entanglement. To rotate the spin of atoms, a kicking laser pulse is used, causing periodic flipping of spins.

If the pulse does not rotate the spins as required, the cubits simply thermalize.

Time crystals, in reality, are not perpetual motion machines, as they do not perform any work. They also do not exist in the ground state or in equilibrium.

Time crystals do not gain or lose energy but travel in motion without losing energy. Thus they do not probably violate the Law of Conservation of Energy.

In Aug, 2020, Time crystals were first discovered to interact at Lancaster University [9]

D. Practical applications of time crystals in the present and future

Time Crystals have emerged as revolutionary concepts which can produce far reaching changes with a variety of present and future applications [10].

Time Crystals can be used in:

- Quantum simulation systems which operate at high temperatures.
- To study complex behavior of matter in the time domain, as has been discussed, would entail the

manifestation of correlations never seen before that would repeat patterns in time.

- In constructing super precise sensors (using diamond or other crystal defects to detect tiny changes in temperature and magnetic fields)
- Quantum computing: Quantum computers , as observed in the Sycamore Processor of Google in 2021, can produce Discrete Time Crystals (DTC), which may lead to vast improvements in quantum computing .,[10]
- Time Travel: Since a Time Crystal breaks the symmetry of time , its atoms are located in different points in space at different points in time, shifting directions, as if a pulsating force separated them. The idea, perhaps, in the future could be used as a possible method for time travel. In a Quantum computer, qubits can travel into a simulated past. Time crystals created in a Quantum computer may behave, while breaking time symmetry, as vehicles enabling travel to the past. as In the science fiction series, Dr. Who, his time travel machine, TARDIS, was powered by time crystals.
- Highly sensitive and precise magnetic field detectors, magnetometers , gyroscopes and atomic clocks

E. Time Crystals and Condensed Matter Physics

Many Body Localization, discussed in a previous section, involves the interaction of symmetry broken states, with the interplay from Chaos to Order. , and is mentioned as the Condensed Matter Physics in time crystals [11]. This is an area where further research remains to be done. The entire concept is constructed from a built in hidden symmetry inside time crystals which is also termed as a phase space lattice symmetry applied in the direction of time. In periodically driven Floquet crystals[12], the discrete time translational symmetry is broken with the onset of disorder or Chaos. Many Body Localization is a stabilizing mechanism leading to Complexity and Order.

Condensed Matter Physics is essentially the study of the properties of matter in the macroscopic and microscopic realms. It explores the concept of matter emerging from the interactions of many atoms and electrons and the physical properties attained as a result of these interactions. In the time domain, these properties may occur as a result of the formation of time crystals as a process of stabilization in the time domain due to Complexity and Order.

IV. CONCLUSION

With the creation of Time Crystals a novel state of matter has been realized. Time Crystals have opened up new avenues of applications of this new material state, analogous to and emulating most or all of the properties in the spatial dimension, but in the time dimension. The applications include quantum systems at higher temperature, quantum computing, highly precise sensors, [4]magnetic field detectors, study of complex and ordered behavior in time, and even possible time travel.

The limitations of Chaos and ordered patterns resulting from Complexity in the time dimension in the process of producing Time Crystals have been elucidated in this paper and bears far reaching results in the future.

One of the primary concepts of ordered stabilization of systems in the time dimension is the Anderson Localization, envisioned by the Nobel Laureate Philip Anderson in 1950. Random fluctuations in spin, caused by the stimulation by a laser pulse in a crystal brings Chaotic disorder. Order sets in with localization, with transition between two states, influenced by a cyclic attractor.

Many Body Localization reserves order between large numbers of interacting particles, whereby the initial state is continued as a result of Complexity followed by order. Transitions (between 1 and 0) occur in a repetitive pattern, governed by a cyclic attractor.

Breaking of Time Translational symmetry, introducing Chaos and subsequent Complexity with order occurs in periodically driven Floquet crystals and thus provides a groundbreaking concept in Condensed Matter Physics, and studies of stability in Non equilibrium systems

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