Article

Testing the orientability of time

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Abstract: A number of experimental tests of time orientability are described as well as clear experimental signatures from non time orientability (time reversal). Some tests are well known, while others are based on more recent theoretical work. Surprisingly, the results all suggest that time is not orientable at a microscopic level; even definitive tests are p ositive. At a microscopic level the direction of time can reverse and a consistent forward time direction cannot be defined. That is the conclusion supported by a range of well-known experiments. The conflict between quantum theory and local realism; electrodynamics with electric charges; and spin half transformation properties of fermions; can all be interpreted as evidence of time reversal. While particle-antiparticle annihilation provides a definitive t est. It offers both a new view of space-time and an novel interpretation of quantum theory with the potential to unify classical and quantum theories.

Keywords: quantum theory;time orientability;time reversal; topology of spacetime

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1. Introduction

It has been suggested that quantum theory may be a manifestation of acausal spacetime structures at a microscopic level. Not only do acausal spacetimes have the same logical structure, exhibiting context dependence, they also offer classical explanations for quantum phenomena such as Spin half and electric charge.

Alternative explanations are rather lacking. After one hundred years quantum theory remains perplexing although the mathematics is undoubtedly correct to an astonishingly high order. One common approach is to just say "That's the way nature is" effectively questioning the need for an explanation. It is indeed not necessary to postulate an underlying reality: quantum theory works well predicting probabilities without the need for a an underlying reality. It is consistent, correct and sufficient for most physicists. But if wee seek an underlying reality to give greater insight, then time reversal offers offers a classical explanation for some of the more perplexing experimental observations.

However appealing or ridiculous acausal spacetimes might seem, it remains a theoretical possibility. Time reversal, more precisely spacetime not being time orientable, is a fundamental property of spacetime. Although it is widely assumed that a consistent forward time direction can be defined everywhere, the question can only be answered through experiment. The orientability is an open question, subject to experimental tests. In this paper the experimental characteristics of a non-time orientable spacetime are outlined and compared with the existing body of experimental evidence.

2. Time Orientability

Orientability of time is a fundamental mathematical property of space-time.. Locally space and time are orientable, the open question is whether the local orientation can be extended continuously on a cosmological and a microscopic scale. There are clear signatures for a lack of time orientability and also definitive tests. Here we review the evidence and the alternative interpretations.

Texts on the structure and topology of space-time[1] raise the question of time orientability. It seems to be a legitimate question to which Hawking and others offer a couple of theoretical arguments why time must be orientable based on the existence of CP violation and on spinor wavefunctions - we will address those arguments later. On the other hand, researchers in quantum gravity expect time to

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behave very strangely at the Plank length scale with concepts such as space-time foam and classical time only appearing as an emergent concept[2]. The concept of orientability requires that spacetime is a differentiable manifold. That is the foundation of general relativity, it is a classical view.

The simplest and most famous example of a non-orientable surface is the Möbius strip. The lack of orientability means that it is not possible to put and x-y coordinate frame all over the surface. Or for a simple test: if Alice and Bob are both right-handed and Alice takes a path round the strip; when she reaches her starting point, she will appear left-handed to Bob. It is an important feature of the experiment that Alice always knows which is her right hand and for her it does not change, she finds Bob left-handed on her return. The Möbius strip is a very simple model for a non orientable two dimensional universe. However we could regard the Möbius band as a space time diagram for a 1D circular space. Now a circuit around the Möbius reverses the time direction; a forward facing time cone appears backward facing, but through the whole journey it was always travelling forward in time.

It should be clear from the examples that a local region is always orientable, the unorientability can only be evident when traversing a non-trivial closed path (it is necessary, but not sufficient, for the path to be non contractible). Our best theory of space and time is general relativity which allows time reversal and closed time-like curves. A cosmological example of a time reversing space-time can be constructed from the de Sitter Universe[1, p181] and simple flat toroidal space-times can be constructed with every combination of closed time-like curves and non orientable space-times. Asymptotically flat space-times can have orientable and non orientable wormholes embedded in them, the Einstein Rosen bridge[3] being the most famous example.

3. A breakdown of causality

Accepting time reversal is to consider space-times that lack the causal structure that we are accustomed to. Most of science is based on, and formulated as, a well-defined initial state evolving under local equations of motion to reach a final state that can be revealed by experiments. Classical physics uses Cauchy surfaces where every timeline passes through the surface exactly once. A Cauchy surface populated with initial date can be used to predict future states using local equations of motion. It is known that such a time-slice cannot be taken for granted in general relativity[1]. A lack of time orientability is one such counterexample to the existence of a Cauchy surface.

If time were not orientable then we would expect to see some physics experiments that could not be explained in the classical way as an initial state evolving under local laws to give a predictable final state. That is exactly what we see in quantum phenomena. Quantum theory describes a world contrary to local realism. It would be normal to quote Aspect's experiments[4] which confirm the violations of Bell's inequalities[5]. But there is only one quantum theory and it cannot be explained as a local realist theory, so every confirmed prediction of quantum theory, not just Aspect's EPR type experiments, confirms that local realism is false.

An equally powerful theorem about the nature of quantum theory is the Kochen-Specker theory[6]. It shows that particle properties consistent with quantum predictions cannot be assigned independently of a future experiment. In other words,: if quantum probabilities are based on an underlying reality then that reality is contextual - it depends upon the future experimental context. Kochen-Specker is a theoretical result; like Bell's inequalities it shows a conflict between local realism and the probabilities predicted by quantum theory.

We know the probabilities predicted by quantum theory are correct. The debate about quantum theory has continued for a hundred years. The accuracy of the probabilistic predictions is confirmed every day, but there are a number of credible interpretations. In essence, they trade off reality against causality. Quantum theory can be considered as evidence for time reversal. And conversely time reversal offers a mechanism and explanation for the non-locality and contextuality of quantum theory[7].

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4. Particle-antiparticle annihilation

A definitive test of the orientability of time should be straightforward. We build a pair of test probes, essentially clocks. One stays in the lab, the other is a probe sent into a region to test it. Like Alice and Bob on the Möbius strip. Then the two clocks are compared. If the region is not orientable, the probe and the lab clock will show time in opposite directions: one will be a normal clock the other will be going backwards.

You might think this means that the probe counts up to a maximum time value and then starts going backwards as it returns to the lab. That is not a valid experiment. It is a requirement of the test that both probes always define a forward time direction. If an observer travelled with the probe, they must see time increasing as measured by their clock. If the clock stops and reverses, then at that instant, time has no direction. Mathematically, the clock must define a non-zero time-like tangent vector.

The signature of time reversal is that, as seen by a lab observer, the probe heads back in time as it exits the region. The lab observer therefore sees both the probe and a backwards counting probe enter the region and disappear. In a sense it looks like a probe and a time reversed probe annihilating each other (see figure 1). Consequently the experimental set up requires a probe and a time-reversed probe to exist and to be sent into the test region. As described in the previous section, an acausal space-time prevents initial data being applied independently of future measurements.

This experiment has been performed. We can use an electron as our probe. A positron is a time reversed electron. They can both be sent into a test region where they appear to annihilate. This signature is identical to a positive test of time reversal. The link between time reversal and charge conjugation is embodied in the powerful CPT theorem which is fundamental to quantum field theory and experimentally verified to a high accuracy.

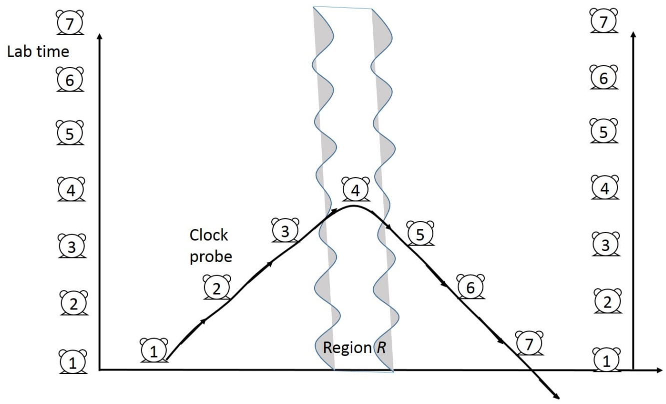

Figure 1. The clock probe counts forward continually, it defines a time direction throughout its path [8]. The observer in the lab sees a backward counting clock and a forward counting clock enter region *R*. The observer sees no clocks after laboratory time = 4.

5. Electric charges

Structures that are not time orientable naturally display net electric charge from source free equations. There are several routes to derive Maxwell's equations of electrodynamics, for example: Kaluza Klein, with an extra compactified space dimension; and using the complex phase of a quantum wavefunction to construct an abelian Yang Mills theory. In fact any construction that adds a phase at each space-time point can be used to derive the source free Maxwell equations. That is a purely classical result. However none of these methods explains electric charges as the source of the fields. Charges, or a charge density, is normally an extra ad-hoc assumption.

By Stokes' theorem The flux through a spherical surface is related to the enclosed charge. The apparent charge is the integrated flux through the surface:

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$$Q_e = \oint_{S^2} \mathbf{E}.\hat{\mathbf{n}} dS = \oint_V \nabla.\mathbf{E} dV \tag{1}$$

For source-free Maxwell's equations, the enclosed charge is zero and the total electric flux is zero. However the sign of **E** is dependent on the time direction (since the electric field three vector as really the time-space components of the antisymmetric Faraday tensor). If the volume, V, is not time orientable, then the volume integral is not well defined and the equality fails. Consequently, there can be net apparent charge from a source free region. This can also be seen by tracing lines of electric flux though a wormhole. Each mouth of the wormhole looks like equal and opposite electric charges. If the wormhole reverses the time direction then each mouth is a charge equal in both magnitude and sign.

The time orientability can do more than explain the appearance of net electric charge, the twisting of the time direction can also be used to define a phase and construct a U(1) bundle to derive the Maxwell equations[9] - in the same way as the theories above, but with the unique feature of explaining the appearance of electric charge.

6. Spin half

A structure that is not time orientable cannot be physically rotated in the normal way [10]. A rotating reference frame can be defined in the lab, but it cannot be extended into a non time orientable region (if it could then the increasing angle as a function of time would define an increasing time direction everywhere - leading to a contradiction). If the lab frame rotates, there must be a fixed surface that does not move. Such a non time orientable space-time would effectively be tethered. A 360 degree rotation of the lab frame would not be a symmetry operation. Because of the topology of the rotation group in 3 dimensions, O(3), a 720 degree rotation would be a symmetry operation (it would be homotopic to the identity). The object would have the transformation properties of a spinor. See for example [11, p1148], [12].

It is not possible to reconcile an object existing in a trivial 3+1 space-time with a 360 degree rotation not being a symmetry operation. In contrast the existence of objects with the transformation properties of a spinor is a signature of a non time orientable space-time.

Fermions are remarkable in that a 360 degree rotation is not a symmetry operation, but a 720 degree rotation is. This is a fascinating group theoretical possibility and leads to a requirement to represent fermions with spinor wavefunctions. Wavefunctions are not directly observable, but there are some interference experiments that highlight the rotational properties of fermions; most famous are the neutron interference results [13]. Consequently, fermions are represented by spinor wavefunctions. The mathematics is consistent and correctly predicts the probabilistic experimental results. The spinor wavefunctions have far reaching implications for quantum field theory, Pauli exclusion principle etc, but fundamentally they are needed to describe the properties of the particles under a rotation.

A realist model of a fermion is incompatible with it being an object in topologically trivial space-time, but it would be expected in a space-time that is not time orientable. Alternatives could be three dimensional topological spaces do not admit rotation vector fields[14].

7. Theoretical arguments for orientability

The question of the orientability of time is asked by other authors, who give a couple of theoretical arguments for believing that it is orientable[1]. One is that we see experimental evidence of time reversal asymmetry in particle physics, but if time reversing regions existed then any forward reaction rate would appear as a reverse reaction rate to a different, time reversed, observer. However this argument ignores the asymmetry in the Universe, which is expanding, and matter dominated - the time reversed observer would see a rather different Universe. The asymmetry in the boundary conditions for any experiment undermine this argument.

A second argument is that we use spinor fields in quantum field theory, but these cannot be defined on a non orientable manifold [15]. Locally any space-time is orientable so for this argument

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to be valid we would need evidence that we could define a spinor field over the whole Universe to rule out cosmological time reversal. Our postulate is that time reversal is a microscopic feature, for the spinor field argument to be valid we would need to have evidence that a spinor field could be defined throughout the interior of an elementary particle. There is no such evidence.

Conversely there are some theoretical arguments suggestive of time reversal. Quantum wavefunctions are used to calculate the probability of experimental results. A distinguishing feature of quantum theory is the expression for the expectation value $< A >$ of a measurement of A for a wavefunction Ψ is:

$$< A > = < \Psi, \hat{A}\Psi > = \int \Psi^* \hat{A} \Psi dV \quad (2)$$

The expression combines both the wavefunction Ψ and the time reversed wavefunction Ψ^*. Arguably, this new definition of probability is at the heart of quantum theory and is the origin of all the non classical results.

In general relativity, the simplest wormhole structures are time reversing: within the event horizon r is the time coordinate and that changes from inward to outward facing through the wormhole mouths[3].

8. Conclusion

Taking the evidence together leads to the startling conclusion that time is not orientable at a microscopic level. A wide variety of distinct quantum phenomena support this conclusion and the lack of a time orientation has the potential to explain perplexing non-classical features of nature. Particle antiparticle annihilation is a definite positive test of time not being orientable.

Surprisingly, it is not tenable to take the contrary view - that time is in fact orientable, and that the evidence has some other explanation. Certainly quantum non-locality, electrodynamics and charge, and spin-half could be interpreted differently or left unexplained. However, particle antiparticle annihilation, is different in character because it is a definitive test of time orientability. If it is dismissed with an alternative explanation, that denies the existence of the definitive test of time orientability. In which case time orientability must be regarded as untestable. Contrary to a mathematical analysis, we would have to say that time orientability is not a physically meaningful concept.

In conclusion we have to either recognise that time is not orientable, or decide that, for physicists, the orientability of time is not a meaningful concept.

9. Implications

Does it matter? Time may not be orientable: is it relevant? We have highlighted some quantum phenomena that could be explained classically with structures that are not time orientable and it certainly leads to a fresh interpretation of quantum theory. It is a potentially fruitful new approach to unification of classical physics, general relativity and quantum theory. For research in differential geometry and general relativity, the orientability and causality of space-time manifolds are often assumed and underpin many theorems. Once the orientability condition is relaxed, there is potential for numerous counterexamples, some of which may have physical significance. It is therefore an insight into the topology of spacetime that could lead to a wealth of new results.

Conflicts of Interest: The author declares no conflict of interest.

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