Quantum Interpretation of the Impedance Model as informed by geometric Clifford algebra

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Abstract: Quantum Interpretations seek to explain observables from formal theory. Impedances govern the flow of energy, are helpful in such attempts. An earlier note documented first efforts to resolve the interpretational ambiguities and contentions from the practical perspective of our model-based approach. In the interim, discovery of the deep connections between the impedance model and geometric Clifford algebra has shed new light on the measurement problem and its manifestations, which we revisit here.

1. Introduction

1.1. Quantum Interpretation

Interpretations of the formalism and phenomenology of quantum mechanics address the distinction between knowledge and reality, between the epistemic and the ontic, between how we know and what we know. It's a pursuit that straddles the boundary between philosophy and physics. There are many areas of contention in the modern dialogue, including reality/observability of the wave function, reality/observability of wave function collapse, determinism and the probabilistic character of wave function collapse, entanglement and non-locality, hidden variables, realism versus the instrumentalism of 'shut up and calculate', the role of the observer,... [1].

In each of these areas of contention quantum interpretations seek to address the same basic question - how is one to understand the canonical measurement problem [2, 3]? How does one get rid of the shifty split [4] of the quantum jump [5], develop a smooth and continuous real-space visualization of state reduction dynamics [6]? What governs the flow of energy and information in collapse of the wave function?

In what follows we present the improved understanding of Quantum Interpretations that has resulted from exploring deep connections between the impedance model and geometric Clifford algebra.

1.2. The Impedance Model

Impedance may be defined as the amplitude and phase of opposition to the flow of energy. Impedances, or more specifically impedance *matching*, governs that flow. In both classical and quantum field theory, impedance must be matched between source and sink for the duration of an interaction to maintain phase coherence and continuity of amplitudes, matched between for instance a photon of a given energy and an electron in a given state [7], .

Classical or quantum, geometric or topological, scale dependent or scale invariant, near field or far field, local or non-local, fermionic or bosonic, mechanical or electromagnetic or gravitational, visible or dark,... impedances govern the flow of energy. The essential point, missing from quantum field theory [8], is that these impedances are quantized [9].

The notion of *exact* impedance quantization extends beyond quantum Hall [10, 11] to impedances corresponding to all potentials. In the impedance approach the possibility of electron geometric structure is studied using a model based upon quantized electromagnetic impedances, written in the language of geometric Clifford algebra [12–14].

The electron is expanded beyond the point, to include the simplest possible geometric objects in one, two, and three dimensions. Point, line, plane, and volume elements, quantized at the electron Compton wavelength and given the attributes of electric and magnetic fields, comprise a minimally complete Pauli algebra of flat 3D space. These fundamental geometric objects are taken to be those of the geometric electron/positron wavefunction [15].

One can calculate quantized impedances associated with elementary particle spectrum observables, the S-matrix [16–20], from interactions between the eight geometric objects of this algebra - one scalar, three vectors, three bivector pseudovectors, and one trivector pseudoscalar. The resulting matrix comprises a Dirac algebra of flat 4D Minkowski spacetime. Elements of the resulting even Pauli subalgebra populate the coupled modes of the elementary particle spectrum. The remaining odd elements are those of transition modes [15].

The point here is that, unlike other interpretations, the present approach has a working electromagnetic geometric model. For input the model requires five fundamental constants - speed of light, Planck's constant, electric charge quantum, permittivity of free space, and electron Compton wavelength [9]. There are no adjustable parameters.

1.3. Geometric Clifford Algebra

Geometric algebra is the 'two-body' algebra of interactions between geometric objects [21]. Interactions are described by the two operations of the geometric product. One (scalar/inner/dot product) is a lowering operator, lowers the dimensionality of one of the two interacting objects. The other (vector/outer/wedge product) raises. For example, from the geometric product of two oriented lines (1D vectors) emerges a point (0D scalar) and an area (2D bivector). To quantize geometric algebra is easy. One simply assigns a length scale to the objects of the algebra.

The serendipitous commonality of geometric objects between the impedance model and geometric algebra has shifted the impedance approach from backcountry to uptown, opening a vast hinterland of new horizons [22]. While Clifford algebra is at the center of theoretical physics, the original intent of geometric interpretation and its potentially helpful intuitive advantage were both lost with the early death of Clifford in the late 19th century and the ascendance of the simpler Gibbs formalism. It lay dormant for over six decades until rediscovered and elaborated by Hestenes [12]. Neither Pauli nor Dirac were aware of the geometric interpretation when inventing their subalgebras.

This fortuitous combination of geometric algebra and impedance quantization makes the present approach unique, opens a new model-based window on attempts to explain emergence of the world we observe from formal quantum theory. In what follows we focus on the remarkable insights available from this perspective.

2. The Measurement Problem

Areas of contention in Quantum Information are, for the most part, manifestations of the measurement problem. A short, simple, and clear definition is given by Wikipedia:

"The measurement problem in quantum mechanics is the problem of how (or whether) wavefunction collapse occurs. The inability to observe this process directly has given rise to many different interpretations of quantum mechanics, and poses a key set of questions that each interpretation must answer." [23]

At root the confusion arises from modeling electrons and quarks as point particles. Points cannot collapse. One cannot understand the decoherence of wavefunction collapse without understanding self-coherence. Presence of the point particle in the Standard Model leaves self-coherence lost in mathematical abstraction, rather than presenting the impedance-driven coherence and decoherence of interacting electromagnetic modes visualized in 4D spacetime.

Particularly significant is the effect the point particle has upon the role of phase in our understanding. Without geometric structure the internal relative phase essential for self-coherence goes ignored, externalized only in the scalar electric charge of the so-called 'gauge particle' and magnetic moment of Dirac's spinor, rather than in the full eight-component Pauli algebra of 3D space.

3. Resolving the Areas of Contention

In what follows we introduce the role of impedances in the most prominent areas of contention.

3.1. Reality and Observability of the Wavefunction

In the impedance approach the wave function is comprised of the fundamental geometric objects shared by geometric algebra and the impedance model, the eight component Pauli algebra of 3D space. These objects are not observable. Their interactions generate the observable S-matrix of the elementary particle spectrum [15–20].

What is abstract in the impedance approach are the objects of Pauli algebra that comprise the wavefunction. What is real are the quantized electromagnetic fields assigned to these geometric objects.

What is abstract is introducing interactions as geometric products of Clifford algebra. What is real is the resulting observable S-matrix. The scattering amplitudes are real [24].

What is abstract is the lone wavefunction, free in the 3D space of Pauli algebra. What is real are interactions of wavefunctions via geometric products to add the dimension of time, to generate 4D spacetime of Dirac algebra.

Although unobservable, just because one can't see it doesn't mean it isn't there. The impedance model lets us calculate observables [15, 24–30], is a model of substantial analytical power. To deny the reality of the wavefunction in this model breaks conservation of energy. The wavefunction is unobservable and real in the impedance approach.

3.2. Reality and Observability of Wavefunction Collapse

Collapse of the wavefunction is easily interpreted in terms of quantum impedances. It follows from decoherence [31, 32], from differential phase shifts between the coupled modes of a given quantum system. The phase shifts are caused by impedances of interactions between geometric objects of wave functions [6]. This is what complex impedances do. They shift phases. Quantum impedances shift quantum phases.

What has been done is to expand the electron/positron Dirac equation beyond scalar electric charge and bivector spin to the full eight fundamental geometric objects of Pauli algebra. The elementary particles are interactions of those objects [26], coupled modes confined by impedance mismatches as one moves away from the particle Compton wavelength. The coupled mode structures correspond to the possible eigenstates, with linear superposition following from time-evolving phase-dependent sharing of energy between modes as governed by Maxwell's equations.

In the impedance approach wave function collapse is real. The collapse itself, the transition mode structure, is not observable. What emerges from collapses are observables [15].

3.3. Determinism and Probabilistic Wave Function Collapse

"... the Schrodinger wave equation determines the wavefunction at any later time. If observers and their measuring apparatus are themselves described by a deterministic wave function, why can we not predict precise results for measurements, but only probabilities? As a general question: How can one establish a correspondence between quantum and classical reality?" [33]

The probabilistic character of quantum mechanics follows from the fact that phase is not a single measurement observable. The measurement extracts the amplitude. The internal phase information of the coherent quantum state is lost as the wave function decoheres. For quantum mechanics to be deterministic one would require phase to be a single measurement observable, which is seemingly impossible[1]. Phase is relative, requires two measurements.

There are both probabilistic and deterministic aspects of impedance quantization.

Probabilistic aspects emerge for instance in the branching ratios [24] and lifetimes [26] of the unstable particles, which are determined by relative impedance matches.

Deterministic aspects are present in the sense that probabilities, these lifetimes and branching ratios, are *determined* by the impedance matches. This *unobservable* determinism removes some of the mystery from 'probabilistic' behavior, illuminates in some small measure the inner workings of the collapse of the wave function.

The general question of correspondence between quantum and classical reality is clarified by moving beyond point particles to the phase coherent internal structure of elementary particles, internal structure that can be visualized as geometric objects of the 3D Pauli algebra of space endowed with electromagnetic fields. The wave function of the impedance model is built from visualizable geometric Clifford algebra.

3.4. Superposition of Quantum States

Investigating the meaning of the newly discovered quantum states of Heisenberg and Schrodinger, Dirac led the way in introducing state space (later to be identified with Hilbert space) to the theory. He defines states as "...the collection of all possible measurement outcomes." [34] According to Dirac, "*The superposition that occurs in quantum mechanics is of an essentially different nature from any occurring in the classical theory"* (italics in original) [35]. What distinguishes quantum superposition from classical is that it is superposition of *states*, of wave *functions*, as opposed for instance to superposition of waves. Waves are observable, wave functions are not.

3.5. Entanglement

"Entanglement is simply Schrodinger's name for superposition in a multiparticle system." [36] Moving beyond the point particle, this is true in any quantum system, be it single or multiparticle. What defines quantum is quantum phase coherence. The existence of a quantum system requires geometry and fields to define the modes, coupling between modes, linear superposition of modes, and phase coherence between modes with phase shifts as appropriate for the couplings. And of course Maxwell's equations.

[1]Though one might consider the possibility that phase, apparently unobservable in a single measurement, seems to flow both forwards and backwards in time [37–43].

This is true for any quantum system, be it the coherent self-entanglement of single free particle modes in linear superposition or the interaction coherence of multiparticle states. Without the correct phases, energy transfer cannot proceed, and superposition is lost. The phases are determined by the mode impedances. This is what quantum impedances do. They shift quantum phase.

3.6. non-Locality

The distinction between non-local and local is clearly established by an understanding of the role of impedances.

The scale invariant impedances (photon far-field, quantum Hall/vector Lorentz, centrifugal, chiral, Coriolis, three body,...) are non-local. With the exception of the massless photon, which has both scale invariant far-field and scale dependent near-field impedances, the invariant impedances cannot do work, cannot transmit energy or information. The resulting direction of motion is perpendicular to the applied force. They only communicate phase, not a single measurement observable. They are the channels linking the entangled eigenstates of non-local state reduction. They cannot be shielded [40, 43]. The invariant impedances are topological. The associated potentials are inverse square.

The scale dependent impedances (photon near-field, Coulomb, dipole, scalar Lorentz,...) are local. They do the work, transmit energy/information. The scale dependent impedances are geometric.

3.7. Hidden Variables

Early on in the development of quantum theory, the probabilistic character prompted Born [44,45] to comment "...anybody dissatisfied with these ideas may feel free to assume that there are additional parameters not yet introduced into the theory which determine the individual event."

If one takes the 'hidden' variables to be quantum phases (not single measurement observables!), then it follows that the "...additional parameters not yet introduced into the theory..." are the phase shifters, the quantum impedances.

3.8. Observer Role

Quantum impedances are background independent. The method of calculating quantum impedances derives from consideration of the two body problem and Mach's principle [28]. There is no observer in the two body problem.

4. Discussion

In the preface to the newly published second edition of his seminal text [13] on the 4D Dirac algebra of geometric Clifford algebra, Professor Hestenes makes four "bold and explicit... claims for innovation" in SpaceTime Algebra:

- STA enables a unified, **co-ordinate free** formulation for all of relativistic physics, including the Dirac equation, Maxwell's equation, and General Relativity.
- Pauli and Dirac matrices are represented in STA as **basis vectors** in space and spacetime respectively, with no necessary connection to spin.
- STA reveals that the **unit imaginary** in quantum mechanics has its origin in spacetime geometry.
- STA reduces the mathematical divide between classical, quantum, and relativistic physics, especially in the use of **rotors** for rotational dynamics and gauge transformations.

The preface encourages making such claims, lest the innovations be overlooked. "Modestly presenting evidence and arguing a case is seldom sufficient." [13] In this spirit, the following five bold and explicit claims are made for the Impedance Approach to quantization:

- IA is **gauge invariant** - Impedances shift phase. Quantum impedances shift quantum phase. In gauge theories phase coherence is maintained by covariant derivatives. In IA coherent phase shifts are introduced by the impedances. IA is gauge invariant.
- IA is **finite** - In IA the quantization scale is taken to be the Compton wavelength. Low and high energy impedance mismatches provide natural cutoffs as one moves away from the quantizaton length. No need to renormalize. IA is finite.

- IA is **confined** - Reflections from the natural cutoffs of the impedance mismatches provide confinement to the vicinity of the quantization length.
- IA is **background independent** - This fundamental connection with STA goes deep, to the **co-ordinate free** formulation essential for quantum gravity [46–48]. In STA, motion is described with respect to the object in question rather than an external coordinate system. Similarly, impedances are calculated from Mach's principle applied to the two body problem [9, 21]. Motion is described with respect to one of the two bodies. IA is background independent. There is no third body, no independent observer to whom rotations can be referenced, only spin.
- IA contains **gravity** - Matching quantized impedances at the Planck scale reveals an exact identity between electromagnetism and gravity [27–30]. By far the most imprecise of the fundamental constants, the gravitational constant G cancels out in the calculations.

5. Summary

The most difficult task in developing the impedance model has proven to be getting physicists to think in terms of impedances. We think quite well in terms of energy, in terms of Lagrangians and Hamiltonians, but historically have overlooked that which governs the flow of that energy [8]. In the present context, quantum impedances provide a new, simple (once the initial unfamiliarity is overcome) and intuitive perspective on interpretations of the quantum phenomenology and formalism.

6. Conclusion

There remains a certain subtle aspect of the measurement problem yet to be addressed in the impedance approach, a wrinkle that appears when examining the origins of proton spin and magnetic moment [15], long an open question in quantum field theory [48–52]. In the impedance approach to proton structure and spin, the anomalous magnetic moment is not an intrinsic property of the proton in free space, but rather an enhancement of precession rate as the proton mode structure is modified by applying the magnetic bias field that defines the spin eigenstates. The problem is to define the boundary of what observables are real in the sense of being intrinsic to a coherent quantum system, and what observables result from the attempt to measure these intrinsic observables [53].

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