Quantum Mechanics without Math

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The study of quantum mechanics requires a lot of difficult mathematics. The main purpose of that math is to calculate predictions for experimental outcomes in the laboratory. But, many of us wish to probe quantum mechanics beneath these "practical" calculations and ask, "What's really going on in the quantum world? " During nearly a century of attempts to answer that question, theorists have proposed many quite different "interpretations" of the mathematics of quantum mechanics. None of these are very convincing, but they are allowed due to under-determination from available relevant experimental constraints. The "Beneath quantum mechanics" realm is still very open and largely awaiting future discoveries. Further progress seems to require that we allow our imaginations to think "way out of the box." Here we refer to what may be in this sub-quantum world in a general way with the use of math symbols and simple expressions but avoiding complex equations.

The topics below include: what "exists?," "psi-field" matter-waves, the importance of complex numbers, and a possible need for time-reversal in the micro-world.

In his discussions on quantum mechanics {"QM" }, Einstein said that the word "**reality**" should encompass two parallel worlds – the observable and the unobservable. The presently unobservable sub-quantum world is what makes the observable world work; but the presently observable world provides few hints about this substratum. It has been a tradition to consider quantum mechanics as only a useful mathematical tool for predicting the results of experimental observations. The "standard" positivistic {*"Copenhagen*"} interpretation forbade asking the question, "What is really going on?" and insisted that one should only talk about what could actually be measured. "Shut up and calculate," and don't conjecture too much.

Quantum mechanics has enjoyed incredible successes since its founding in 1926 – its procedures work very well! Its standard formulation is based on a set of postulates whose applications involve a lot of "higher math" so that its study is considered lengthy and difficult. Seriously inquiring about a possible "reality" beneath those postulates has generally been frustrating and unproductive with many strongly different views. To overcome this apparent barrier to understanding how Nature works at the quantum level, we will first be forced to question our conventional human biases; are we blocking ourselves from understanding?

The pre-1960's tradition of avoiding fresh speculations was finally weakened due a major breakthrough by John Bell in 1964 and the eventually pervasive appearance of what are called "entanglements" between particles that have interacted in the past. Quantum mechanics was already very strange, but lots of "spooky action at a distance" was almost too strange.

If you are one of those people who want to know about the sub-world that makes it work rather than how to precisely calculate laboratory results, then you may enter a different and open world of "philosophy of physics" that might not require so much math. There is a world of things we do not understand about quantum mechanics, and it can be more interesting to talk about them rather than only studying the framework we think we do know.

Existence:

A leading view is that entities that exist physically should be associated with observable consequences – the ability to interact with other physical "realities." It should be "empirical" as being derived from observation or experiment. And the term is usually meant to exclude "existence" in the mind. But consider: do Newton's and Maxwell's laws exist? {they can predict results from experiments}. Does time exist? Does space-time curvature exist? Does the quantum Vacuum exist? Does energy and momentum exist? Do abstract electrons and photons exist? Does mathematics exist? *{I say "yes" to all of these – mathematics in a somewhat* <u>*different*</u> *sense where "existence" means total logical consistency of something with the body of math. And useful structures like that await rediscovery by intelligences dispersed throughout the universe.}.*

Energy is the King of concepts in physics. But it took a lot of difficult creative work over a long time to come up with the law saying that, despite its many forms, <u>total energy is conserved.</u> One could say that matter exists because it has energy equivalence, $E = mc^2$. Electric and magnetic fields "exist" because their energy density is measured by E^2 and B^2. They also exert forces on charged particles, and that has objective consequences.

For the quantum world, we need different definitions of what it means to exist– to be real. For example, many would say that quantum <u>fields</u> are primary. The term "reality" has usually meant "classically-real" – but quantum mechanics is largely deemed to be <u>non</u>-classical. Many physicists confusingly talk past each other because of the ambiguity of the word "real." So, a first step towards clarity should be to use a different term to encompass the presently unobservable world of sub-quantum mechanics such as *"quantum-real," qu-real, or "Q-real."* It is largely up to future thinkers and experimenters to attempt a consensus on defining that world, and that will require some new and very convincing data and logical arguments.

Part of the realm of the Q-real might end up not being falsifiable physics but *hopefully some sort of 'respectable'* <u>metaphysics</u> – "beyond present physics." What does that mean?

> *"**Metaphysics** is the branch of philosophy that studies the first principles of being, identity and change, space and time, causality, necessity and possibility" [Wikipedia]. The primary question in metaphysics is "What is the true nature of reality. "The line between metaphysics and physics is often blurry; but as a rough guide, one can think of a theory's metaphysics as those foundational assumptions made in its interpretation that are not usually directly tested in experiment."*

Unfortunately, the name "metaphysics" can be misleading because it has been used and misused for millennia so that it now means somewhat different things to different people – a Greek origin near 400 BCE and development in the Middle Ages. The term "<u>*ontology*</u>*" is better defined and is a proper-subset of metaphysics. Ontology is the study of what things exist and what kinds of things they are. To be useful, ontology and metaphysics must be tied to known physics as closely as possible.*

> *A frequently mentioned and enduring ontology is Plato's "theory of* <u>*Forms*</u>*" as pure universal concepts abstracted beyond experience by use of reason. The essence of a Form is invariance: spaceless, timeless, unchangeable "ideas." A perfect circle is a Form, and many mathematical ideas are Platonic Forms. Electrons may be ideal Forms because they are the same invariant "identical particles" everywhere throughout the universe.*
>
> *But all of us would be hard pressed to say what an electron IS or even what a photon IS. Electron "spin" is a key attribute of the quantum world but also an idea very hard for us to grasp. We imagine a ball that is spinning – except that it isn't a ball and it isn't spinning. But we would all say that particle-spin is a very basic concept in modern physics. Its existence is unquestioned – but its definition is somewhat opaque.*

The various *<u>interpretations</u>* *of quantum mechanics are often associated with many unstated metaphysical biases. Despite that, today's metaphysics may lead to tomorrow's new physics; and the "unobserved" today needn't be "unobservable" forever.*

Over the past century, there have been a great many new experiments and new interpretations that help to extend and clarify the realm and limits of the quantum world. As just a few examples of progress:

In 1952, David Bohm presented a breakthrough interpretation of QM that is functionally equivalent to the traditional 1926 "Copenhagen" interpretation of Bohr and Heisenberg. It says that "particles" and their positions can actually exist along a selected "trajectory" {position being called a nonlocal "hidden variable"}. For the two-slit interference experiment, a matter wave goes through both but a "particle" only goes through one. The wave-function ψ serves as a guiding or "pilot-wave" field for the path of a particle, so wave-and-particle can coexist together. It accomplished theoretically what canonical QM believed to be impossible.

{This interpretation now has a slowly growing persistent minority following, but I choose to not discuss it much here. Eventually, the "particle" might be replaced with a de Broglie "soliton"—a moving fixed-shape local wave. The word "soliton" didn't exist in de Broglie's time}.

In 1964, John Bell was inspired by Bohm and proposed his quantum "Bell-Tests" which later on experimentally demonstrated that there are no "<u>local</u> hidden variables." This led us to largely believe now that QM is "non-local" with the frequent appearance of "entanglements" -- instantaneous "spooky actions-at-a-distance" {Einstein} *—but what is called instantaneous in one frame of reference may just be called superluminal or "faster than the speed of light" in another. Neither of these is allowed in a special relativity in which time only goes forward.*

The once dominant "Copenhagen interpretation" is now falling out of favor, and "philosophers of physics today almost unanimously reject it." Adam Becker said, "It is gibberish, unintelligible." And Lee Smolin said, "I don't think there are many enthusiastic followers of Bohr left alive."

Another, so-called "Objective Collapse" interpretation *{or spontaneous collapse, e.g., "GRW," 1986}* might well be subject to future experimental tests -- a falsifiable theory.

Quantum experiments have pushed out the limits of the quantum realm:
Perhaps the most impressive are that quantum entanglements seem unaffected by long-distance separations between particles and that very large molecules also act like waves that can interfere with themselves *{component energies and masses are additive, so frequencies are also additive to a summed frequency representing total mass}.*

At present the longest distance for entanglement-teleportation is 1400 kilometers! and the biggest quantum interfering molecules are 25,000 times more massive than a hydrogen atom. We are also now producing atoms "orbited" by electrons very far away with over a thousand wave nodes and an orbit circumference totaling nearly half a millimeter! *{almost macroscopic and called "Rydberg atoms" with principle quantum number n = 1200 }.* Experiments are also now often being performed with individual **single** photons and single electrons showing that the previous "ensemble-only Interpretation" of QM was too restrictive -- QM also applies to single particles.

Still, it may be that some arenas will be forever untestable. That is likely true for "String Theory" and may be true for some core of sub-quantum-mechanics. It may even be that some foundations of "Classical Physics" are really not well understood.

A central assumption in what follows is that there are things that should be placed into the Q-real bucket *against the grain of the old "Copenhagen interpretation of quantum mechanics.* I would like to think that we should already be able to list some Q-real ingredients such as the existence of "matter waves" – but there are presently big stumbling blocks to doing so: unknown mechanisms for the probabilistic random selection of individual outcomes; "particle-wave duality;" behavior of "identical particles; and many strong differences of opinion about the proper "interpretation of quantum mechanics."

"Matter Waves:"

The information about what can be known in a quantum experiment is encoded in a mathematical object called the "wave-function" or "matter-wave" named for its source: matter or mass energy *{the "m" in $E = mc^2$},* other kinetic or potential energies or all together. All particles or fields that possess energy can also show matter waves. A moving particle of mass m possesses a wavelength "lambda" $\lambda = h/mv$ and a frequency $f = E/h$ *(with the rest-mass frequency portion $f_o = m_o c^2/h$ then being discarded for non-relativistic QM in its key "Schrodinger" equation for quantum waves).* A developing majority opinion on what is called "particle-wave duality" is that particle and wave natures do not exist at the same time. When a tiny object is traveling, it is a wave; when it interacts, it can behave as if it were a small particle *{or at least our deduction of a particle nature because many now say that there are no "particles" at all ! – only special "fields" and their excitations – and this is actually an "axiom" of quantum field theory which is deeper than QM }.*

A major example and "big clue" to beliefs about waves versus particles is the atomic nucleus conundrum: If protons and neutrons in a nucleus were pictured as little balls of experimentally confirmed diameters *(a la Linus Pauling type stacked ball models),* they would be packed so closely together that no ball could interpenetrate them! It is easy to believe in a "ball shape" for nucleons since they act as a "bag" for a rich quark-gluon soupy interior with sizes determined by electron scattering experiments. But, n's and p's and α's also seem to speed around fairly freely inside the 'dense' nucleus and can organize themselves in an angular-momentum "shell model" hierarchy **as if they were all "really waves"** rather than particles! The "particle" ball shape may only apply during measurement interactions. *Clarify this paradox (is it non-interaction due to different sets of angular momentum quantum numbers?).*

A major postulate of standard quantum mechanics is the "Schrodinger equation" *{Erwin Schrödinger, 1926}.* It is a "special" kind of "wave equation" that only describes ideal wave-aspects of "particles" -- how they wiggle, how they develop and how they can attenuate. The solutions to Schrodinger's equation are "wave functions" usually labeled by the Greek letter psi {"ψ" or $\psi(\mathbf{x},t)$ or "ket" psi = $|\psi\rangle$ in Dirac's notation}. From the beginning, there has been a major problem of interpreting the "real nature" of psi.

An old quote is,

"Erwin With His Psi Can Do Calculations Quite A Few.
But One Thing Has Not Been Seen Just What Does Psi Really Mean?"

It is wrong to say that a traveling electron is just a wave -- electrons have mass, charge, spin, and magnetic moments. But, we put those attributes not into the wave (where they probably "really" belong for "physical" waves) but by hand into energy terms (potential energy experienced by charges when they are present or magnetic moments interacting with magnetic fields). We don't need to really assign those attributes to a localized particle, a more spaced-out electron-quantum-field knows all of them.

The Schrodinger equation begins with a statement of conservation of total energy as kinetic energy of motion plus potential energies of position (*"E = KE + PE" -- a math equation -- but I am going to assume that very simple relations or symbols should be acceptable in this note)*. The solutions can be waves that satisfy the input energy conditions as they vary over space and time; and most of the time, the chosen potential energies are electromagnetic.

My perspective is: *the starting point of quantum mechanics and its matter field* is that the total mass-energy of a "particle" is identical to a basic localized rest-vibration of very high frequency, *f* . *I call "**E = hf**" "postulate zero," where h is called Planck's constant*. "*h" is a very tiny conversion number – but that's because we ourselves are relatively huge and use units like meters and seconds which are way too big to describe the micro-world of particles*). E = hf goes by several different names such as "The Planck or Einstein or de Broglie relation" *[Ref. #1]. There are many different quantum fields, one for each kind of particle; but all of them share this "matter-field" property.*

What is it that is vibrating? It is common to just call it a primitive matter-field without any further discussion – not quite like anything familiar in our world. It is vaguely like a ticking clock without the clock. It is claimed that the all-pervasive "vacuum Higgs field" gives mass to some of the elementary particles, {*so perhaps fundamental frequency is due to a rapid cycling of "hypercharge" between an electron and the omnipresent Higgs Field? Making this clearer is a goal of future physics}.* At present there is no explanation for any of the values of the particular masses possessed by fundamental particles nor for their extreme range in values from 0.5 "electron volts" to 173,000 million electron volts of energy.

The other key ingredient of quantum mechanics *{like an accompanying postulate zero-prime' for matter fields}* is that "particles" do begin to act like waves with a wavelength "λ " when seen by an observer in relative motion *{ "lambda" = λ = h/ mv, where v is relative velocity)*. Where does this come from? Quantum wave mechanics is non-relativistic *{QM = "NR-QM" },* but it originated with a Frenchman named de Broglie who derived his wavelength relation from Einstein's theory of special relativity in 1924. Now, relativity theory also requires a lot of math, but some of its results are very simple and well known: clocks in motion appear to tick more slowly – the duration of a second "dilates." And moving rods with relatively rapid speed appear to get shorter to an observer:

{Old Limerick: "There once was a fencer named Fisk, whose thrust was exceedingly brisk;
so fast was his action the Fitzgerald contraction reduced his rapier to a disk"}.

Special Relativity says that the velocity of light is a constant that is the upper limit to "particle" speeds. No matter what relative motion there is between a source and an observer, the measured speed of light will always be seen as just one speed *(called **"c"** for 'celerity' ~ 3 x 10^8 meters per second).* Gravitational waves were also recently revealed to travel with this same light speed c.

All uniformly moving frames of reference are declared to be only relative so that the laws of physics are the same regardless of motion. A frame of reference moving near light speed will experience almost no time duration and no distance traveled (a photon just "snaps its fingers" and can suddenly appear a billion light years away).

From concepts like these, we obtain formulas that can mathematically transform quantities from one inertial frame to another for not just distance and time but also frequency and velocity and energy and a bunch of other basic variables *{called "4-vectors" for the 4-dimensional 'space-time' considered as a merged entity. Usual "vectors" are 3-vectors in space}.* In the case of interest here, we can view a particle's fundamental frequency with relative speed v and see it transformed into a wave with a wavelength. The faster a particle moves, the shorter its wavelength becomes

{In physics language, we say, "for a relative velocity v between inertial frames, the "Lorentz transformation" of a rest-mass frequency results in a moving particle now possessing wavelength λ = h divided by "momentum" mv so that as v increases, λ decreases}.

This is <u>not</u> like a bobbing cork on water causing a wavelength of outgoing water waves – it is something uniquely relativistic. In addition, the frequency also increases a bit in value due to kinetic energy being added onto the rest mass of a particle *{That is Einstein's* $E = mc^2 = hf$ *where E = rest mass-energy plus kinetic energy}.* QM energy is <u>coded</u> into the 'density of waves in time,' and mv momentum is represented by the 'density of waves in space.' *{Is there a mechanism in the space-time Vacuum that performs and processes "de-coding" ? Also, for more than one particle at a time, how does Nature's Vacuum enforce conservation of energy-momentum? That requirement is related to entanglement-correlations.}.*

Since the Schrodinger equation is supposed to be only non-relativistic with "particle" speeds well below light speed, it throws away the rest-mass vibration and only keep kinetic and potential energies. These are placed into the math machinery of the Schrodinger equation to calculate a well-defined "wave" for a given system as it evolves prior to some final "measurement."

That also means that the equation does <u>not</u> apply to light which, at light speed, is <u>always</u> relativistic. A "wave-function" for light lacks "positions" and usually deals with other attributes like polarizations or angular momentum.

Quantum mechanics traditionally added that "psi" as a function of space and time, ψ=ψ(**x**,t), is not a "real" wave but rather a strange and complex "**amplitude**" for the probability of finding a particle along with one of its particulate properties materializing somewhere at the end of its "trajectories." *{Notice that many terms here are in quotation marks "_" because their precise meaning often differs from our common usages}.* ψ as <u>a "probability amplitude"</u> was a brand new concept and was accompanied by another brand-new *ad hoc* end concept called "collapse" of the wave function to reveal some particle properties.

Also added on is another very important postulate called the **"Born Rule"** saying that we have to <u>square</u> these amplitudes to get to usual probabilities *{the future probability of becoming a measured particle is provided by |psi| squared {*$\psi \rightarrow |\psi|^2 = \psi^*\psi$*}.* <u>Why</u> do we have to square psi to get probabilities? – no one knows – and no one knows why <u>probabilities</u> of outcomes over random distributions or even "why quanta" – these are properties of the "matter field." None of this is in the Schrodinger equation – these are additions imposed on the calculational framework so that one can get the right answers in the lab.

Suppose that we think of going from psi to final collapse of the wave function in steps:

1. Find psi ψ(x,t) as a solution to the Schrodinger differential equation;
2. justify forming psi squared $|\psi|^2$ – *why the Born Rule?;*
3. Then try to imagine a mechanism for selecting one outcome out of a random variable probability distribution {choosing a spacetime-actuality from a set of quantum potentialities}. Usually we have one particle in, so we materialize one particle-quanta out.

The name "probability amplitude" for ψ is a label for the nature of its <u>combined</u> steps towards final outcomes "for all practical purposes" {"FAPP"} rather than any separate intrinsic reality of ψ. Psi could have been called a "pre-energy existence amplitude"

There is one interpretation of quantum mechanics that does try to address the origin of the Born Rule.

The "transactional interpretation" of QM ["TI," Cramer 1986] proposes that ψ by itself is an outgoing "offer wave" from an "emitter" towards many possible "absorbers" which then each respond by re-emitting a special "psi-star," ψ*, wave "backwards in time" to the source along with some "hand-shaking" agreement that naturally leads to two applications of ψ to give a $|\psi|^2$ intensity (two-hands clapping – and just one hand by itself won't produce any noise). This is about the only interpretation that motivates the Born Rule and enables picturing many quantum phenomena for photons -- but it isn't yet very popular and not well developed for massive particles. The basic requirement is that "the wave equations describing the particles of interest must, like the electromagnetic wave equation, have both advanced and retarded solutions" -- the relevant equations should have time symmetry. Going backwards in time is strange to our sensibilities and alien to our "classical" physics views.

{Many classical equations of physics are "time reversible" for time becoming negative, t→ "- t". The classical "Arrow of Time" towards the "future" is not yet explained. Sometimes it is associated with the claim that the early universe had very low "entropy" and that we live in an "entropy-gradient" towards increasing future "disorder."}.

And how can the quantum world select a particular outcome for each detected particle? What is the hidden process in "quantum-land?" Well, the intensity $|\psi\ (x,t)|^2$ is certainly a participant. And, as a guess, perhaps the outgoing "offer wave" encounters each potential "absorber" with a particular "constructive phase matching" of some sort so that some encounters are preferentially encouraged *{one sort of phase is how far along a sine wave we go – the angle θ in sine(θ) }.* Phase differences, *Δθ,* are useful and important, but phase by itself is considered "unreal" in present quantum mechanics.

In agreement with this, a recent article by Carver Mead [Mead, 2020] demystifies randomness and collapse using phase and frequency matching between electromagnetic "waves" and atoms and the phase coherence of the advanced-retarded handshake. Examples are worked out in mathematical detail and result in a "nonlinear avalanche" bringing about a transaction. This is a welcome addition to the transactional interpretation.

An important concept in math and physics is "field." A field is a quantity that assigns a value to every point of space or space-time. Sometimes we use the symbol **x** as short for 3-dimensions of space, (x, y, & z together). So, for example, a "temperature field" assigns a number degree of hot or cold to every point, T(**x**,t), in an environment or on a map. An electric field **E**(**x**,t) assigns a vector arrow to every point in its domain. A wave function, ψ= ψ(**x**,t), is a field that assigns a complex number called "amplitude" to each point of a "wave." There are other possible types of "numbers" that represent fields beyond scalar number fields, vector fields, and complex fields *(for example: tensors and "spinors" and "operator-valued fields").* ψ for an electron might be called the "electron square root of probability field" {Wilczek}. For the case of two particles, we might need two copies of space for an effective total of 6 spatial dimensions: ψ(**x, x'**, t) *{the "configuration- space" problem}.* This is very hard to picture, and it is hard to understand how the two spaces interact.

An important question that is never asked is how and in what sense the Vacuum of space-time can hold so many values: each of its many fields has numbers or "magnitudes" or something at each space-time point. What are these fields and how can they hold and process so many numbers or their physical equivalent? Having extra dimensions to make Nature more complex might be helpful but is not yet proven, and string theory is struggling these days. In addition, the Vacuum with its many quantum fields knows the masses and charges and spins and much more for each particle stimulated out of the vacuum fields. If more and more energy is pumped into a point, increasingly more massive particles can be produced (simple quark-and-anti-quark “mesons,” strong and anti-strong particles, charm mesons, bottom mesons, … up to “heavy-photons” (the Z^o “weak” boson). And the Vacuum seems to know all the physical constants and laws of the universe too and does so in the same way everywhere throughout the universe.

{For times greater than a pico-second ABB (After the Big Bang), particles could only be produced along with their anti-particles – not separately. So, the creation of an electron as an excitation also requires the creation of an accompanying positron excitation. But there are many electrons left over prior to this time}.

{Capitalize the word “Vacuum” because it refers not to the empty classical vacuum devoid of things but rather more like the superposition of all quantum fields somehow together -- the potential for “everything” and thus perhaps the most important “thing” in physics—even though you can’t see it}.

The simplest understanding for an outward propagation of values (e.g. waves) might be “cellular automata” with the Vacuum pictured as an array or lattice of many small cubic-cells each holding values. If one cell suddenly changes its value, all the adjoining cells perform new averages of their adjoining cells to propagate new values outwards until some equilibrium is achieved (a standard technique in numerical analysis). Propagation of electric potential fields, $\phi(\mathbf{x},t)$, can be calculated by this sort of over-and-over-again cell-averaging, and the propagation of values occurs at the speed of light in vacuum.

Going Deeper Down :

As humans living in a “classical” world, we have strong biases about what is acceptably “real.” Our imaginations are severely limited by our lengthy animal past. But quantum mechanics should require that we start thinking very unconventional thoughts.

Niels Bohr once said, “We agree his theory is crazy; but is it crazy enough to be true? ”

One way to think out of the box is to move beyond mathematics with real numbers. Complex numbers presently have a lot of use in our worldly math – but they have often been considered as calculational conveniences rather than “real.” But complex numbers are required in quantum mechanics – beyond just convenience. ψ(x,t) is postulated to be a complex number; and, as such, can always be expressed in terms of a magnitude and a phase angle.

{Complex numbers have parts based on the square root of -1 called “ i ” for “imaginary”—in retrospect, a poor choice of name. So, we may have z = x + i y for a complex number. Frank Wilczek said, “complex numbers are God’s numbers.” The Schrodinger equation is not a typical wave equation, it is more like a special “heat or diffusion equation,” $u_t = \nabla^2 u$, with complex variables that allow wave solutions – for example, by assuming that time is “imaginary” as was done in early special relativity}. The “amplitude,” psi, is complex numbers. Complex numbers allow quantum “tunneling,” the ability of an electron to penetrate a potential barrier higher than its kinetic energy. This would not be allowed in classical mechanics.

When we start to talk about electron “spin,” we have to go even deeper.

Electron spin is best described by something called “quaternion” mathematics where there are three basic complex square roots of minus one—three imaginary bases.

(In 1843, they were originally called i, j, and k which later became the symbols for x,y,z- axis units for 3d geometry. Experiments with electron spins could be used to “derive” the “hypercomplex” quaternions again}.

Even this was a little strange for us, so we switched to a more “convenient” convention of using square 2 x 2 “Pauli matrices” -- which have a basis of three separate square-roots of PLUS one).

And then in 1928, Paul Dirac essentially took the square-root of a simplest relativistic wave equation and found that he needed to create something new called 4x4 “gamma matrices” which are funny numbers with square roots of both -1’s and +1’s. At this level of depth, for the first time, we could reveal and talk about new physical properties such as “antimatter.” We depend on these strange numbers in "quantum field theory." We've only scratched the surface of how deep we really need to go for more advanced fields.

Quantum mechanics is about what happens to a fixed number of given particles already in existence. The discipline called Quantum Field Theory ("QFT") is more encompassing and based on relativity: energy and mass are equivalent and interchangeable – particles can be created and destroyed as long as total mass-energy is finally conserved; an accelerated charge can give off photons. A neutral pion can decay into two oppositely directed gamma-rays. A gamma ray encountering an atom can convert itself into an electron-positron pair (new matter balanced by new anti-matter).

There are quantum fields "deeper" than electrons and electromagnetism, and their mathematics can be much more complex. There is a quantum field for each elementary matter particle and force *{e, μ, τ leptons; u,d,s,c,b, t quarks; 8 gluons, neutrinos, the photon γ , W^+,W^-, Z^o weak particles, and the Higgs field and particle, H}.* Many fields are naturally coupled with other fields. For example, the electron-field and the electromagnetic (photon) field are coupled together with a small coupling constant called alpha = $\alpha \simeq 1/137$ *{ = $e^2/2\epsilon_o hc$ < 1% }* allowing electrons to emit and absorb photons *{and physicist's emails and passwords and locks to include the prime number 137}.* Shaking an electron can radiate electromagnetic photons. All electrons throughout the universe are identical because they are all excitations of the same universal "electron-field." And this applies also to all of the other types of "elementary" particles. Quarks and gluons couple very strongly together so that we could talk about protons and neutrons as almost having quantum fields of their own. So, all protons in the "observable" universe *(perhaps 10^{79} of them)* are identical because they are all excitations of the same universal "proton field."

The key attribute of the word "particle" is that of being positioned and "localized" within some small volume of space. A particle as a "field-excitation" is different – its "bulk" may be localized, but it always has a tail that extends far. There is no "principle of complete localization" in quantum field theory. And, "in quantum field theory, all field variables in any one region of spacetime are entangled with variables in other regions. *{the Reeh-Schlieder theorem, Witten 2018}* .

If we are willing to agree to such complexity and use of complex numbers in the quantum world, we should also be willing to entertain the unconventional idea that microworld "particle-waves" may also be able to go backwards in time.

Entanglement : **Long Range Correlations Revealed Instantly:**

In the arena of "entanglement," we have the appearance of long-range agreements between two particles. In 1935, Schrodinger said that entanglement "is not one but the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought" *{But, it took a long time to really catch on—like the 1990's!}.* It can be expressed in a wavefunction as "a superposition of alternatives so that the final state of one particle depends on the input state of the other." Apparent "spooky action at a distance" has been demonstrated beyond a thousand kilometers as if distance simply didn't matter! The math is simple, but the actualities are mind boggling! So far, there are only two ideas to explain this: one is having particles connected by some sort of quantum "wormholes" – an idea sounding like desperation. The other is the back-and-forth in time "transactional" idea. Maybe a final transactional path or "world line" is transferable like say a lightning strike with current going back and forth multiple times within each bolt. Probably something else is the cause – but it might be beyond present imaginations.

There are a variety of ways to entangle particles: Two things being in the same place or same path at the same time. Passing an ultraviolet photon through a special crystal can produce two new entangled photons of lower energy. A two-step down decay of an excited atom [e.g., see [Orzel]]. The annihilation of a positron with an electron produces two entangled gamma ray photons as also does pion decay *{$\pi^o \rightarrow \gamma+\gamma$ }.*

In superconductivity, two conduction electrons moving in opposite directions at a speed of a million meters per second exchange an acoustic phonon and become an entangled "Cooper" pair. A "single electron transistor can split these to give two separated entangled electrons. Entanglements can be transferred from one particle to another {like from electrons to photons or photons to electrons or photons to photons. An enlightening article a while back was called, "Entanglement <u>swapping</u> between two particles that never coexisted." Entanglement can also be created between photons with "<u>orbital</u> angular momentum!" *{"OAM"}.* Linearly polarized photons have electric fields going up and down. Circularly polarized photons have E-fields in a spiral shape carrying a spin of one *{$S = \pm 1\ \hbar$ }.* OAM light has interleaved helical shapes with any allowed angular momentum and a "hole" in the center of a beam *{ "ℓ " = $-2\hbar$, -1, +1, $+2\hbar$, + ….}.* One way to imagine this is to have say 3 equally spaced out +charges on a rapidly rotating pinwheel. These charges "drag electromagnetic space" *(the vector potential **A**-field)* and propagate outwards at the speed of light as 3 interleaved helixes.

One of the first experimental tests with entanglement was in the early 1980s. A beam of calcium atoms or mercury atoms were excited to a higher state above normal in a way that two consecutive decays were needed to get back to the usual ground state. Each decay from higher orbits gives off a photon of some color (like a green photon or a blue photon). And then a few nanoseconds later the second decay gives off another photon in an opposite direction. Coming from the same atom at about the same time means that the two photons are correlated or entangled with each other. If the polarization of one photon is known, the other photon's direction of polarization is also determined. But, in a first pass through time, these assignments do not exist until actual detection.

The end state of the photon absorption can depend on the polarization of the photons, so "since the polarizations are indeterminate-but-correlated, you will end up with two atoms whose states are indeterminate-but-correlated." In practice, this is kind of tricky, since the sorts of entangled photons one can generate easily don't connect readily "to atomic states that last a long time. If you're clever, though, you can find ways to do this kind of thing, and convert entanglement of photons into entanglement of distant atoms that absorb those photons."

Chinese scientists have just shattered a record in quantum **<u>teleportation</u>** by sending packets of information *{ the quantum state of a photon as how it is polarized}* from Tibet to a satellite in orbit 870 miles above the Earth's surface. Such transmissions don't have to be in free space. Entanglements have also been demonstrated via single-photon interference through optical fiber "over dozens of kilometers."

One of the biggest arguments against the reality of the wavefunction is the case of ψ for two or more particles together. Each particle moves in 3-space so that two particles seem to require 2×3-space. What does a wave look like in 6 dimensions?

But, if two particles share a previous interaction vertex, V, then we can have a back-and-forth in time **"zigzag"** connecting action along both paths through the vertex [deBeauregard 1947, Cramer 1986]. The case of an ultraviolet photon from a UV laser beam {frequency = f_{uv}} splitting into two lower frequency colors {e.g., $f_{green} \simeq f_{uv}/2$ } gives two newly created entangled photons. We can't see waves in 6-dimensions, but can look at correlations between the actions of two particles such as these two photons. What we sometimes see is interference patterns for each photon being correlated with the other such that the overlapping interference is that expected from the original higher energy UV beam. Each photon knows and behaves in accordance with the other. Just because we can't picture it well doesn't mean that it isn't "real."

The Ψ Field:

*One view [Hobson] is that "Schrodinger's Ψ(**x**,t) is a spatially extended field representing the amplitude for an electron (i.e., the electron-positron field) to interact at **x** rather than an amplitude for finding, upon measurement, the so-called "particle." Fields are all there is."… "quanta are not particles; they are excitations of spatially unbounded fields." …"QFT puts matter on the same all-fields footing as radiation."… "the Dirac field IS the electron."*

An electron is an "excitation out of the electron-field" which permeates the space-time "Vacuum." The source of its matter field is the mass-energy of the particle "represented" by its fundamental vibration. What is the relationship between the electron as field excitation and as its matter wave?

As a first trial view, suppose the electron as electron-field excitation has a size and a spatial shape like say a "bell" or Gaussian profile as a "cloud" surrounding a "particle" and falling off with radial distance r in some way. Label the shape as φ(**x**,t) over space and time as something like a potential field similar to that of the electric potential field from a charge – but smooth rather than "cuspy." Could electron as φ attain a size at least as big as the separation of a two-slit-mask so that parts of the same shape could go through both slits. The answer is NO. Having a small shape is a particle versus wave view. It is the associated matter-wave ψ that goes through both slits. And since φ represents a particle, it has no frequency or wavelength itself except throughout its surrounding ψ field. No source talks about a matter field coupling to quantum fields – somehow it is just a "given."

"What we mean by the size of an electron is the size of the particle that one would observe in some detection process – an interaction. How would one be able to determine this size? Typically, the detection process is a scattering process [Stack]." The electron size must be smaller than the size associated with the highest energy of the experiment, and that turns out to be essentially zero! That is, in high-energy physics, the electron is a "point-particle" with no size. But some useful sizes associated with the electron are bigger than this: the "classical electron radius" r_e=2.82 fm; its Compton wavelength r_c = 386 fm; and the first "Bohr orbit" a_o = 53 pm *{where prefix p in pico-meters = 10^{-12}, f = femto- = 10^{-15}, and $r_e = \alpha\, r_c = \alpha^2 a_o$ with alpha ≃ 1/137}.*
{ Shift now to low energy: "in the non-relativistic limit, the Dirac electron appears not as a point charge, but as a distribution of charge and current extending over a domain of Compton wavelength" {Messiah II Text}.

All of these sizes are still much smaller than typical distances between slits for interference experiments. So, now, forget φ and deal with the reality of ψ .

Matter and localized energy content are the same thing, so a "matter field" *in some form* also "represents" an energy field that itself also "represents" physical "existence." Superimposed on this is the field frequency and a de Broglie relation as vector $\mathbf{p} = \hbar\mathbf{k} = (h/2\pi)\cdot(2\pi/\lambda) = h/\lambda$ – the wavenumber k and wavelength λ have a direction in the direction of motion. This is a picture for a single particle as a wave. ψ can interact and be modified by the presence of other particles or larger objects. Most importantly, it interacts and changes shape with imposed potential fields V(x,t) in the Schrodinger equation.

What we often picture in classes is a wavefunction as a tapered "wave-packet" moving at velocity v. We have a somewhat localized wave-packet when we forcibly try to constrain the ψ field of φ to a constricted location that imposes matter-field frequency components above and below base frequency f to form the packet shape (called a "preparation of ψ"). It doesn't want to be constrained. When it is then allowed to move freely, high frequency components move faster than low frequency components causing the packet to spread out quickly with time. This spreading can become huge with ψ still <u>considered to be a holistic entity</u>. This is very hard on our intuition: the packet can stretch very far making amplitudes seemingly negligible – and still deliver a quanta of energy.

So now, from a relative velocity v, we have a ψ wavelength λ from the relativistic transform of a fundamental vibration f representing particle mass and something like an amplitude profile from calculating ψ .

As an experimental example, an electron beam current inside an electron microscope can be severely attenuated down to only about one electron at a time. Let the wavefunction for these single electrons next encounter <u>either</u> an etched thin double-slit mask <u>or</u> a charged conducting cross-wire – your choice. The single ψ can then split into two new side-by-side ψ-beam paths that can later be brought back together at a detector. The result is a multi-peaked two-slit interference pattern [e.g.,Bach]. The slits can be separated by several thousand electron wavelengths, <u>and ψ still goes through both!</u> Several experimental demonstrations of this have been **called <u>"the most beautiful experiment in physics!"</u>**

{For instance: for multiple interference fringes, λ_e ~ 50 pm=h/p, energy KE = 600 eV, beam spot size ~ 0.5-14 nm, width of biprism-wire or 2-slit separation perhaps D∼280 nm, slits width 50 nm, height 4μm, v=0.05c, D/λ ~ 5600 wavelengths<u>. The ψ field has significant width</u>.}.

The scalar matter wave ψ can be much longer and wider than these: like the above example where part of it goes through two slits and like the high Bohr orbits as in the Rydberg atoms. Orbits are stationary waves – we could say that the electron wave reinforces itself every time it "circles." So, if the matter-field around an "electron excitation," φ(r), had a small weak tail, it would step on itself with each pass and build it up into a standing wave around a circle. If the wave is in a "wave-packet," it elongates quickly with time and can become long enough to encompass a big Rydberg circle. That is, for an "orbit," a wave-packet can step on itself and reinforce itself with each circular "pass" so that its summed profile over many passes can become more lengthy and uniform – like a circular wave.

{-- a somewht oversimplified picture. Instead of "circle-waves," actual "orbits" in general are more like parts of what you see when you punch a water balloon – "spherical harmonics." There is a "back-and-forth" mode plus an "up-and-down" mode plus circular waves and more – a superposition of many modes – e.g., video at https://www.youtube.com/watch?v=jn5KuSHguUE}.

An e-beam can be made to curve under the influence of electric and magnetic fields according to a force F = ma = q_e(E + v×B) so that acceleration is a = (q_e/m)(E+v×B). That is, path-bending depends on the <u>ratio</u> of charge, q, to mass, **q/m or "e/m"** *{J.J. Thomson discovered the electron by measuring this e/m ratio in 1897}.* In the electron microscope beam, the single-electron ψ-field can be large and wider than the beam. Schrodinger believed that time-independent standing-wave charge was really spread out in an electron density eψ*ψ – and that picture seems to work well for bound-system molecular and solid-state physics. So, for an electron in the beam, are its electron charge and mass centrally located or spread out in ψ with each little volume having a proportional increment of charge Δq and mass Δm? An answer is that it wouldn't matter when the response has the same uniform ratio, Δq/ Δm = q_e/m. The bending is the same.

A big question is what happens when a single ψ "splits"? A single electron wave hitting a two-slit mask is mainly just absorbed on the mask maybe with some bounceback and only tiny "signals" making it through the two slits, $\psi \rightarrow \psi_1+\psi_2$. These two little "Huygen wavelet" beams can be brought back together for interference with bending and focusing EM fields if their $\Delta q/\Delta m=q/m$ ratios are constant. But, with now tiny Δq's and Δm's, how can a new single electron quanta end up in the interference detectors? We seem to be back into orthodoxy with ψ being a probability amplitude for materialization of "particles" at detectors. Each wavelet has three things: a frequency as a code for energy, a wavelength as a code for momentum and an amplitude for full-quanta-materialization. When a wave splits, it is the local amplitude that diminishes. There is still a conundrum that if charge and mass are diffuse throughout ψ , are they "real" or just a quantum simulation of some sort prior to detections. The quantum world likes to explore all of its possible outcomes holistically "prior" to deciding on one actual outcome. Kaku says this is like a Copenhagen postulate, "Before an observation is made, an object exists in all possible states simultaneously."

Still, if we think of some mass and charge in every part of an electron wavefunction and the wave splits into two or more separated waves, it is hard to imagine how they still function and collapse into a single quanta somewhere. There must be some connectedness between parts that we cannot see.

{As Roger Penrose says, "different parts of the wave cannot be thought of as local disturbances, each carrying on independently of what is happening in a remote region. Wavefunctions have a strongly non-local character; in this sense they are completely holistic entities" [Penrose, 2005]}.

There are interpretations that allow wavefunctions to spontaneously "collapse" *{materialize as quanta*} on their own in different ways such as a likely collapse when interacting with increasingly large masses such as detectors *{e.g., "CSL," 1989}.* There is even a recent interpretation that says that a wavefunction is "a description of random discontinuous motion of particles" *["RDM," Gao]* meaning random collapses all the time according to $|\psi|^2$ probability all over the wave-function. Note that these rapid materializing flickerings will "time average" as little dm's and dq's everywhere so that bending would be the same as just diffuse mass and charge. All of these interpretations require new collapse terms added onto the usual Schrodinger equation – but any such alterations present new problems.

It is commonly believed that quantum fields "fluctuate" and contribute to "vacuum energy." But that {zero-point ground} energy cannot be measured and can arbitrarily be chosen to be zero. It is true that electric fields fluctuate, but that's not clear for matter fields. One confusion is that if we measure how many particles are in a multi-particle state, we will get a number; but it will change randomly from measurement to measurement. The state itself can be fixed, but randomness in measurement can give the appearance of a fluctuation where none may "actually" exist.

This is a contentious issue. In general, fluctuations should be <u>intense</u> and strongly affect the cosmological constant in cosmology – but that doesn't happen. On the other hand, small quantum electrodynamics effects of fluctuations have been very well validated and measured to many decimal points in agreement with theory. A standard view is, "Quantum fields never quite maintain a constant value; their value at any point in space is always jittering around a bit. This jitter is called "quantum fluctuations", … and is a consequence of the famous "uncertainty principle" of Heisenberg [Strassler]." Once one debates quantum mechanics apart from just its successful mathematics, there are an awful lot of contentious issues.

For the case of light, its *matter field* is a related to its vector potential **A**-field with its accompanying E and B fields because they both represent types of "energy" – "energy-fields." Light even as a single photon field can be split in many ways (e.g., an optical beam splitter), and a full energy photon could materialize from either beam. …Nature uses its frequency and wavelength to deliver required quanta of either energy or momentum to a target while "amplitude" gives its probability.

Time Reversal:

Many of the basic equations of physics such as in Newtonian physics or electromagnetism work equally well with time going either forwards or backwards – this is called "T symmetry: t→ -t ". From this, we would not expect to have any arrow of time. But thermodynamics for large systems says that "entropy" as statistical disorder always increases forward in time and is effectively an equivalent arrow for time.

From our experiences, it seems "natural to say that particles which have interacted in the recent past are not independent." And we easily believe that prior to interactions, there are no microscopic correlations – we have an asymmetric bias for future over past which Price calls "micro-innocence." He adds, "what should we expect the world to be like if there were no asymmetry of μ-Innocence — if, at the microscopic level, interacting systems were correlated in the same way both before and after their interaction?

Remarkably enough, it seems that the right answer to this question may be this one: We should expect the world to be the kind of world we find in quantum mechanics [Price]." Regarding the strangeness of quantum measurements, Maudlin adds, "if we envision (incorrectly, in my opinion) the measurement by allowing the measurement apparatus to appear suddenly, 'out of thin air,' we have a problem in both QM and QFT." But in the old traditional view, Bohr said that "reality is somehow indeterminate until a measurement is made"— a measurement interaction forces reality to take on a definite condition, where none existed before – a biased forward time progression. And John Bell said that -- quantum mechanics seems to have non-local influences – in apparent violation of relativity. We are now "so used to talk of nonlocality and indeterminacy in quantum mechanics that they no longer seem entirely absurd." "Familiarity has bred contentment in physics, and the reductio has lost its absurdum."

The term retrocausality "is intended to cover any metaphysical picture in which future events are regarded as having some sort of influence on past events." But in quantum mechanics, the Schrodinger equation assumes that time only goes forward. However, if we deduce the Schrodinger equation backwards from the broader theories of "relativistic quantum mechanics" or "quantum electrodynamics" we end up with two Schrodinger equations: the usual default one for time going forward and another for time going backwards. This is the starting point for the "Transactional Interpretation of Quantum Mechanics" or "TI."

As previously mentioned, the usual wave function, ψ, is an "offer wave" from a source to potential absorbers, each of which are stimulated to propagate "confirmation waves," ψ*, backwards in time to the source according to the time reversed Schrodinger equation. The joining of the two waves yields the Born rule for probability, ψ*ψ [Cramer 1986]. The source somehow randomly selects a chosen absorber for a final transaction and transfer of energy and momentum from a source to the absorber. Actual acts of emission and absorption are fundamentally relativistic processes beyond usual QM. Most published examples of TI are for photons traveling at the speed of light. But John Cramer also intends this for matter waves as well. It may also be the most promising explanation of entanglements.

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