Beneath Copenhagen Quantum Mechanics

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Recent popular books on the status of quantum interpretations and "reality" are saying that the Copenhagen Paradigm of Quantum Mechanics {"standard textbook QM"} is being questioned as never before and found to be lacking in many ways [e.g., Becker]. For a century, it has enabled reliable calculations for experimental tests; but it fails to tell a story about how the world works and sometimes even declares that there is no story to tell. Its main support was the early 1900's philosophy of Logical Positivism {"only statements verifiable through direct observation or logical proof are meaningful in terms of conveying truth"}. Thomas Kuhn's 1962 thesis on scientific revolutions led to the fall of positivism among philosophers – but that awareness in physics took additional decades. The pilot wave interpretation of Bohm and de Broglie was a more "real" philosophy later supported by John Bell. Experiments violating the "Bell Inequality" now emphasize that QM entanglements are **non-local** – seemingly having instantaneous "action at a distance." Entanglements in quantum computing may be a multi-billion dollar business but are based on actions that make no intuitive sense. The number of interpretations is increasing and none are being refuted.

The central problem here is that if Copenhagen is a poor interpretation, **where is any consensus on replacing it in terms of telling a better and more realistic story?** A goal of this note is to suggest some weak spots in canonical quantum mechanics that might be better explored towards improved understandings of underlying mechanisms not provided in textbooks. An overview is first presented, and that is then followed by more elaborate discussions.

In addition to the standard postulates of quantum mechanics, one could suggest some guidelines that might aid a deeper understanding.

A. **Quantum Reality:** Acknowledge that Nature has its own mechanisms which enable the functioning of "standard QM" and that the rules of this realm are distinctly different from the classical domain (e.g., the world of **ψ** versus $|\psi|^2$) . This means that the Bohr/Heisenberg insistence on classical observers was right *in my opinion*; but their declaration that there is no quantum reality is an unnecessary impediment to understandings. A truth to separation of realms would discourage a current claim of "all quantum" in which the classical world also obeys QM. Standard QM defines ψ as "waves of probability" with an unfortunate implication of being intrinsically unreal. That makes some sense if output events were truly random. But suppose amplitudes represented "presence" along with a hidden mechanism that physically selected output events. That would make ψ more "quantum real." Quantum Reality doesn't have to be "in spacetime" (we have a multitude of "simultaneous possibilities," reversibility of time, and 4-"vectors" in terms of complex and hypercomplex numbers rather than "reals."

B. **Primacy of Path Integrals:** Feynman's Sum Over Paths formulation says that the amplitude of a transition between initial and final states of a quantum system is described by considering all possible paths that a particle can take and summing their contributions. There is a quantum superposition of alternative space-time histories. In simpler terms, each electron explores all possibilities, and the world of its possibilities is quantum-real. The Schrodinger equation can be derived from a path integral; but it has its electromagnetic interactions with particle properties expressed in its energy Hamiltonian operator, $\hat{H}$. The path integral does that via its scalar Lagrangian, $\mathcal{L}$. That is the mathematics but not necessarily all of the "physics."

C. **<u>The Wave-function, psi, is indeed a summary of "our knowledge" but is also partly real:</u>** ψ is a mathematical expression allowing calculation of experimental outcomes; but, by itself, ψ does not contain any particle properties – only the result of them having been there. Its waves are real in the quantum world of "amplitudes." But the more deeply real quantum "physical" waves and mechanisms must include some particle property aspects to enable ongoing interactions with experimental electromagnetic potentials {e.g., apparently full electron charge expressed in a superposition of spatial locations}. We might perhaps use notation <u>W(x,t) for the underlying physical "wavicle"</u> versus the summary function $\psi(x,t)$ that emphasizes "our knowledge." For the particle attribute of electron spin, we have "spinors" $\chi=(^a{}_b)$ for spin up vs spin down. This has the property $\chi^\dagger\chi = a^*a + b^*b = 1$ so that chi resembles not spin but rather an "amplitude for spin." Something like that may be needed for the particle charge attribute for W {QFT should provide deeper clues; but, in QFT, spatial position variable x "isn't an observable at all" – it doesn't care where a "particle" is *..if "particles" even exist at all*}. Charge "e" is a coupling constant for electron- photon electromagnetic interactions.

D. **Standard <u>non-relativistic QM</u> depends on relativity**: quantum amplitude phase $\phi = \mathbf{k}\cdot\mathbf{x} - \omega t = -\omega_o\tau = K_\mu X^\mu$ is a relativistic invariant where $|\vec{\mathbf{k}}| = 2\pi/\lambda$ and $\omega_o = m_o c^2/\hbar$. de Broglie's famous relation $\mathbf{p = h/\lambda}$ is **<u>derived</u>** from a Lorentz transformation of a fundamental de Broglie "tone" $f_o=\omega_o/2\pi = m_o c^2/h$ *{for a relatively moving frame of reference with velocity v}.* An electron "tone" is an extended nonpropagating wave having the same instantaneous phase everywhere! In quantum field theory {QFT}, an elementary particle is an excitation of a quantum field and inherits particle properties from its universal quantum field. A quanta, such as an electron, is a highly-unified <u>spatially-extended</u> non-localized bundle of quantized field energy.

E. **"Single-particle entanglement" of wave portions:** A splitting of a de Broglie wave (or "tone" in its center-of-mass frame) results in a spatial superposition of multiple waves where each part is holistically connected to the other. An example is a single de Broglie electron wave split by a charged thin wire such as an "electron beam-splitter." Each part can be made to coherently interfere with the other later-on downstream. Technically, the term entanglement usually refers to multi-particle interactions.

F. **<u>There have to be sub-quantum mechanisms for the enforcement of conservation laws</u>**: Physicists presently just assume observers will always see proper enforcement. Energy is the king of concepts in physics – and Hamiltonians and Lagrangians just assume a conservation outcome. For scatterings into multiple branches, conservation may have to be negotiated. Bell's theorem says that this arrangement is not pre-arranged.

G. <u>**The Transactional Interpretation**</u> of Quantum Mechanics postulates emitter waves , ψ, and absorber acknowledgment waves, ψ*, going forwards and backwards in time to form a transaction [Cramer][TI]. This seems to be a necessary mechanism to: a) explain two-particle entanglement (communicating back in time to a common splitting point), b) explaining the **Born** rule {a transaction has ψ*ψ}, and c) providing a mechanism for negotiating between multiple outcomes to ensure <u>satisfying conservation laws.</u> In addition, the nonlinear mathematics demonstrates a **selection** mechanism for observational "collapse" of a wave packet, ψ(x,t) – i.e., exploiting a fortuitous phase matching between emitter and absorber phases [Carver Mead]. Now it is also suggested for single entanglement between parts of a single split wave-function $\alpha\psi(x_1,t)+\beta\psi(x_2,t)$*… {…or towards an observer as* $(1/\sqrt{2})[|0\,1\rangle+|1\,0\rangle]$ *-- occupied vs unoccupied rays}.* So far, the only other suggested but poorly-defined mechanism is "quantum wormholes" between emitters and entangled absorbers. Some mechanism similar to but broader and more imaginative than transactions and wormholes is likely needed.

H. <u>**Inconsistent language and definitions:**</u> Differing interpretations lead to different definitions of basic terms such as measurement, collapse, non-locality, "particle," "wave," "observer," being <u>**in**</u> space-time, … e.g., [Wikipedia] "Quantum measurement is "the manipulation or testing of a physical system to produce a numerical result" *{which didn't <u>exist until</u> it was measured}.* An example is a Stern-Gerlach projection of an electron into an upper beam changing its quantum state by a "collapse" to "spin-up" *{it is now measured!}.* <u>But</u>, an "observer" won't <u>know</u> this until it is "detected" *{with a "classical" apparatus, and then the state is "gone" and maybe localized "particle-ness" is seen }.* For a discussion of the important and persistent "measurement problem," see [Sabine].

Broader Discussions:

In trying to "understand" quantum mechanics, perhaps the biggest conceptual problem is how <u>single particle properties</u> such as charge, magnetic moment, and fermion spin are deduced to have been fully expressed in multiple places at once (e.g., superpositions of the actions due to full charge, **e**, in the multiple ray waves emanating from multiple interference slits). We usually think of electrons as point particles having charge along with de Broglie waves with wavelength λ = h/p, and we predict their behavior using the Schrodinger equation. The Feynman "sum over histories" formulation of QM imagines single charged particles taking all possible pathways as a superposition searching for "least action." Instead of particles, it is intuitively easier to imagine waves forming little Huygen's wavelets everywhere in space-time. But, in some sense, these wavelets have to be "wavicles" with some representation of particle properties. This superposition over spatial positions is one magical non-intuitive aspect of quantum mechanics.

The de Broglie sitting "cloud" or "tone" of pure vibration, $f_o = E_o/h = m_o c^2/h$ might be imagined as a diffuse blob of vibration in its own center-of-mass sitting reference frame. As such, a free particle might conveniently be pictured as a Gaussian $\exp(-r^2/2\sigma^2)$. "Size" ~ σ here, doesn't imply tiny observed detected sizes but rather extents in the realm of quantum "amplitude" presence. The blob for a free <u>electron must be big enough to go through multiple slits</u> in interference tests. A more extreme example is the huge encompassing extent of "Rydberg atom orbitals" when n > 100. In other words, size must be at least microns. That size for electrons and even for most composite particles encompasses a majority of real experimental examples [dp5-24] .

Another magical ingredient of quantum behavior is the scattering of a blob into parts by interactions. An example is the splitting of a single electron tone into two parts in superposition which is accomplished by moving a negatively charged thin wire through it (like an electron bi-prism in an electron microscope). In most actual electron interference (or any matter-wave interference) experiments, the two parts of the blob are never very far apart (usually less than a micron separation). Quantum mechanics allows for diverging wave-fronts which can move apart by arbitrarily large distances while still being interpreted as probability amplitudes for observing an electron particle in any fractional part. For all practical purposes (FAPP), could it make sense to only allow microns of separation for real experiments -- is there a test that says otherwise?

Actually, **Yes!** **Neutron Mach-Zehnder** silicon crystal interferometry can result in de Broglie beam-path separation of one to five centimeters! It would seem that **distance of separation doesn't matter**. These parts are still portions of a holistic electron particle entity; and there must be a physical mechanism enabling that (something similar to single-particle parts entanglement). We are already familiar with large distances not mattering in tests of the entanglement of two photons.

Perhaps the simplest example of the need for superpositions of locations of an electron charge is the Aharonov-Bohm effect {"AB"} on double slit interference. A full particle charge e is needed by both slit-rays for e$\vec{\mathbf{A}}$ adding to and subtracting from particle momentum **p**=mV resulting in a shift in fringe locations. The example of a charged-wire electron beam splitter also requires the presence of electron charge in de Broglie rays on both sides of the wire for the repulsive splitting of paths even when only one electron is present at a time in a beam. There are other examples such as neutron magnetic moments and spin seeming to be in multiple separate paths [Lemmel]. Some say that a particle investigates all possibilities and takes on all possible paths in superpositions; and that is consistent with the "path-integral" formulation of quantum mechanics. For that to make sense as a particle wave exploration requires that the wave is more than just a Schrodinger wave representing only probability amplitudes which itself doesn't include any particle properties. It must be more like a "wavicle" W(x,t). And, instead of large waves of probability applicable to each single particle, perhaps the probability wave function really represents an ensemble of separate de Broglie objects each having limited extent.

The major problem then reduces to how separated blob-fractions retain their holistic integrity – something resembling "single particle entanglement." One {still unpopular} solution is "retrocausality" where the separate parts are tied back in time to the separating event of parts to their previous single entity {that somewhat avoids nonlocality since the separating event is local – *but at a later "pseudotime."* The other solution (also intended for multi-particle entanglements) is communication via quantum "wormholes." Neither alternative yet has community acceptance.

The Quantum Domain

Stephen Weinberg once asked a professor, Phil, about the fate of a once promising physics student. "Phil shook his head sadly and said, "He tried to understand quantum mechanics."

> *Physicists generally acknowledge this warning. But, here, I still wish to make one more fools' attempt at it. That doesn't require acceptance of standard rules but rather trying to find a modestly deeper level of explanation or state the core of the mystery. Perhaps the greatest magic is the ability of a single particle field to split into parts while retaining its holistic wave and effective particle properties in all separated parts.*

> "Tell me, Mr. Bernstein, in our store, should we sell soda and seltzers?
> Well…. "In the hot weather, people are thirsty. On the other hand, such an item can be bought on the streets as well. … So, … we mustn't be too quick to say this or that."
> *final Lines from the movie "Hester Street" set in 1896. … Immigrant woman "Gitl" talking to a Talmudic scholar.* [script]

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Part A: Matter Waves for Single Particles Introduction:

Over the last century, we've heard and argued about a great many conflicting stories concerning the interpretation of quantum mechanics. Many of the stories seem plausible and lead us to be unable to arrive at any consensus decision for a single prescribed story. Rather than approaching resolution, the number of possible interpretations continues to grow.

Does the wave-function **ψ** represent "our knowledge" about a statistical ensemble of events (a mathematical summary of what we could expect if we were to make measurements on the system). Or does it represent actually-existing causal entities. The intransigent mixture of both of these together is called the "Quantum Omelette" {[Jaynes], see Appendix below}, and making progress demands that we somehow unscramble the mix. Some simply state that that is impossible.

In the Copenhagen Interpretation, a few essential features of single-particle quantum mechanics to dissect are: "wave-particle duality," probability amplitudes, superpositions of amplitudes, the Born rule, and unitary development followed by purely random collapses."

There is now a vast treasure trove of many hundreds of new experimental test publications on quantum mechanics and entanglements (e.g., the "Vienna group" and a Nobel prize to Anton Zeilinger). Assimilating and processing these will percolate throughout the physics community and should alter philosophical understandings and interpretations.

In discussing "Quantum Realism," it is usually stated that there are two separate realities: classical and quantum – the reality of the world of amplitudes or possibilities. The historical and prolonged convention is that "reality" means classical reality, and that leads to great confusion when discussing quantum mechanics (e.g., the Copenhagen interpretation unreality of ψ as "dogma"). But in a world that increasingly acknowledges quantum mechanics as foundational, the mechanisms underlying and being used by Nature are also real whether we can grasp them or not. This is not yet a majority view, and that's a problem. The quantum world ("quantumland") is a realm of amplitudes in which all alternative possibilities are explored via "superpositions" [e.g., Pursehouse]. Classical reality includes the set of final results either from "random collapses" or hidden selection mechanisms.

A goal here is to come up with a more intuitive understanding of quantum mechanics where the term "intuitive" doesn't have to mean classical, and interpretations don't have to be a random choice from a menu of present offerings. But there are still basic QM properties that insist on being mysterious and even outlandish. Our minds have difficulty imagining physical processes "outside of spacetime." So, is it at all possible to picture a "particle" as an extended and malleable fuzzy object (perhaps a blob as large as a micron?).

As an initial step here, reconsider the old term "wave-particle duality" {"WPD"} by trying to break ψ into parts such as the domain of more primitive de Broglie matter-waves {"D"} and the domain of actual matter "particles" properties {"X"}. Elementary particles are extended excitations of their particular quantum fields" *{think X-itations}.* Experimental conditions may sometimes demonstrate wave properties as dominant and others may reveal a particle nature (such as the photo-electric effect for ultra-violet waves). X and D might be immiscible since "D" may live in the world of "amplitudes" while X concepts are viewed as being more classical.

Revealing a more intuitive sense of the WP-duality is regarded as a tough nut with a common view is that a rational interpretation is impossible in principle, that there are no macroscopic analogs, and that Born's probabilistic interpretation is needed. Some believe that both "waves" and "particles" are merely mathematical abstractions. Bohr might say that objects are wavelike when not observed and particle-like when they are observed. A Copenhagen and Bohmian view is that de Broglie waves are already probability waves and are devoid of any particle property such as mass, charge, or spin almost by definition. That is not clearly apparent because spin-amplitudes as represented by "spinors" are often attached to ψ; mass as mass-energy is already coded into the frequency of dB-waves {$E = hf = mc^2$}; and charge must somehow go along with and throughout the wave as is indicated in the Aharonov-Bohm effect {more about that below}. If we step up to Quantum Field Theory (QFT), then a "wave" is identified as a superposition of an indefinite number of particles. They come, and they go. The "field" is primary, and the electron is a quantum of the field [Tong]. But then, we have to face the puzzle of large molecule wave interference – a bigger conceptual challenge. The existence of de Broglie waves for huge molecule particles should have an impact on our beliefs about quantum mechanics. But, perhaps we should not wildly extrapolate to saying that baseballs also have wavelengths -- extreme extrapolations do occur in the realm of quantum mechanics interpretations.

At least for particles below visible sizes, it is a strange realization that highly composite matter particles possess dB-vibrations and dB-waves (ω and k) where the vibration frequency represents the <u>sum</u> of <u>all</u> the mass energy of the particle. At this level, energy <u>is</u> a vibration, and a collective excitation "X" applies. All {small} masses are sources for a <u>vibrating energy field</u>. This is generic – independent of composition or the specific types of fermion or boson quantum fields.

<u>Sample experimental values regarding particle matter wave extents, LIST:</u>

Cases for electron $\delta_{dB}(x,t)$ through two slits with transverse separation between slits {⊥ to $\vec{v}$}
~ Δy_{max} ~ 500 nm {and experiment slit widths near 200 nm}.
C_{60} molecules through double slits (e.g., **Figs. 1a, 1b** below), $\Delta y \leq 0.1$ µm [dp5-24, Nonlocality].
And distance to detection screen {interference path length} L= 125 cm [Arndt]. When test wavelengths are targeted to be near a picometer (λ~ 1pm), manufactured distance between slits may be D ~ 50- 100 nm – a hundred times larger than the molecule size (~1 nm, and D/λ ~ 10^5).

Rydberg atom orbital size up to 10 µm! as a circular standing wave (Bohr quantum number n ~ 100). {… and much bigger n values of over 1200 have been observed! "The largest Rydberg atoms can be tens or hundreds of micrometers in size and can even approach the size of a period at the end of a sentence." *-- a huge domain for dBB tones and waves.* The case of huge Rydberg orbitals is most revealing. To enable standing-wave-reinforcements over a large distance implies that the "tone" cloud is also at least that big too. }

Typical electron beam biprism "wire" splitter diameters: 80 nm, 120 nm, 400 nm, 500 nm…
Electron microscope longitudinal coherence length ~ 0.4 to 0.7 µm.
Mach-Zehnder interference [MZI} path length (6-10 keV electrons) ~ ℓ_{sum} ~ 5 cm.
MZ slow neutrons in Si-crystal interferometer path length L ~ 10 cm. Another was 50 cm.
Neutron beam separations: λ 10.2 nm L 50cm **separation 1.2 cm** WIDE!
λ 135 pm, L = 21 cm, 6 SiO_2 plates, **separation 5.0 cm ‼**
λ 190 pm, $\theta_{Bragg} = 30^o$. Separation of paths is centimeters.

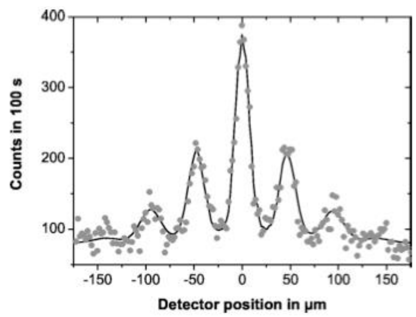
The longest tested de Broglie matter co-linear **wave-lengths** are usually below a nanometer: λ =167 pm (Davisson-Germer, 54 eV electrons), 180 pm (thermal 25 meV neutrons), and 459 pm (Na_2 170 µeV molecules). For wave trains, multiple wavelengths added together may extend well beyond nanometers; and these trains are still part of the dB-tone cloud extent.

In contrast, photon bosons derive from the universal electromagnetic-quantum-field rather than matter fields, and their wavelengths can be huge (1 kHz radio wave, λ = 300 km!). Photons are not de Broglie matter-waves.

Multi-particle **Entanglement**: Researchers in Germany have demonstrated quantum entanglement of two [rubidium atoms kept in optical traps in two different buildings] separated by **33 km** (20.5 miles) of fiber optics. This is a record distance for this kind of "communication" and marks a breakthrough towards a fast and secure quantum internet.

Two recently published research papers detail the generation of a **27-qubit** genuine multipartite entangled state and, separately, the generation of a 65-qubit bipartite entangled state. Greenberger-Horne-Zeilinger (GHZ) on n qubits as $(|0\rangle^n + |1\rangle^n)/\sqrt{2}$. [Australia][IBM]. Such states are sometimes called "Cat States," an equal superposition of being all zeros or all ones (like a dead or alive cat).

Actual separation for Stern-Gerlach output e-beams: original test ~ 0.2 mm on collector {developed using bad-sulfurous-cigar smoke}. Tests now use a hot Pt wire detector.



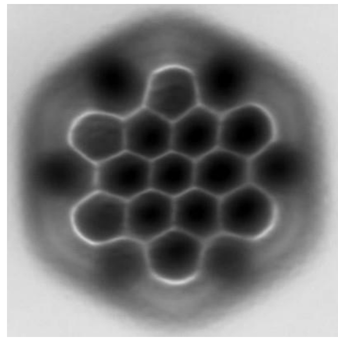


Figure 1a: Sample result of double slit interference pattern for C60 "buckyball" large molecules. {Far field diffraction, Zeilinger, Am. J. Phys., Vol. 71, No. 4, April 2003}.
Figure 1b: Atomic Force Microscope **AFM** flattened 2d picture of the atoms and bonds of a C60 molecule. https://www.nature.com/articles/nnano.2012.178 {a "particle"!}.

Some Key Facts From Relativity: $\vec{k}$, $\vec{A}$ and **p** may be considered as consequences of Lorentz transformations {"LT"} between frames in relative motion, $\vec{V}$, of ω, ϕ, and Energy, E. That is, 4-vectors: $(\omega_o, 0)$ →LT→ $(\omega,\vec{k})$, $(E_o,0)$→LT→$(E,\vec{p})$ and $(\phi_o,0)$→LT→$(\phi,\vec{A})$.
These are inter-related by $E = hf = \hbar\omega$, $E_o=m_oc^2=hf_o$, and a **derived** $p = h/\lambda = \hbar k$. If potential ϕ_o is a Coulomb field, then vector potential $\vec{A}$ represents a Coulomb field in motion.
[see more detailed Math derivations in Appendix below].

A persistent question is whether sub-quantum-mechanics "exists-in-spacetime." LT's are indeed a spacetime transformation. But sub-QM is time reversible, so the usual "arrow of time" need not be honored. The cohesiveness or holistic-ness of the spread-out domain of particle properties and wave of single quantum particle seems to be "outside of space-time" standard rules but perhaps consistent with quantum field theory. de Broglie tones have spread-out perfect phase (not lost with distance).

Multiplying electromagnetic potentials by an electron charge gives electric potential energy and what Maxwell called "electromagnetic momentum," $p_{em} = e\mathbf{A}$. So now, the 4-vectors $(E_{em},0)=(e\phi_o,0)$ → LT → $(e\phi, e\vec{A})$. The presence of this can be observed via interference peak phase shifting of peaks in the Aharonov-Bohm effect. This, in turn, implies that particle charge has a presence in a superposition of locations (e.g., weighing amplitudes in rays from both slits simultaneously). Since charge couples to the electromagnetic quantum field; and the Schrodinger (or "Pauli" equation) expresses conservation of energy as:

$$(^1/_{2m})\{(\hat{\mathbf{p}} - e\vec{\mathbf{A}})^2 - e\hbar\boldsymbol{\sigma}\cdot\mathbf{B} + e\phi\}\psi = E\psi = i\hbar\partial\psi/\partial t\ .$$

{So, an electron wavefunction ψ(x,t) is altered by the presence of externally applied $\vec{A}$, $\vec{B}$, and scalar ϕ(x) fields of an experimental system environment– they are not considered "part of" ψ but they determine its final expression}. Note that Bohmian mechanics uses the same wave function as the Schrödinger equation. It just processes it differently.

For example, if we begin considering an electron wavefunction for a given momentum $\vec{p}_o$ at (x=0,t=0)) and place a rotary A field at x = 2 and another Coulomb ϕ field at x = 4, we can obtain an encompassing wavefunction over all x=0 to 10 where a detector perhaps awaits. But charge e must have some sort of "presence" at x=2 and x=4 to feel those fields as the wave goes by. There is a similar case for neutron spin and magnetic moment particle attributes in its own interferomentry tests.

For more-than-one-particle [Part B later], a key realization is that there has to be mechanisms for the enforcement of conservation laws in scatterings. Entanglements and waves in configuration space are involved but need to be explained and interpreted.

The Schrodinger equation dovetails particle energy in an environment of potential energy fields H(KE, PE), with waves, Ψ(k,ω), while ignoring relativistic mass-energy as a convenient simplification. What is the degree and manner of coupling of a naïve "particle" to its wave-cloud – is a particle in its wave or only a result and deduction of "collapse"?

Consider further the labeled categories of the three inter-related topics D, X, and Ψ -- with de Broglie waves labeled as $\delta_{dB}(x,t) \in \Psi$.

"D" – for de Broglie-- includes relevant mass-energy-frequencies and wavelengths which depend on relative velocities. There may be a spatial range of influence of sitting "tones, ω_o" *as a "particle-matter-energy existence cloud".* For particular instances in motion, $\delta_{dB}(x,t)$'s $\simeq$ $e^{i\phi}$ =exp[i(**k·x**-ωt)] = $exp[-i\omega_o\tau]$ ∈ D *{phase* $d\phi = K \cdot dX = k_\mu dx^\mu$ *is a relativistic invariant}.* D is "real" in amplitude space, but it might be more narrowly defined than ψ. Again, the term "real" here is more than just "classical;" it refers to all mechanism that Nature uses to make quantum mechanics work. Nature decides – not us. One virtue of the "tone" view is that splitting of a de Broglie wave into parts during interferometry experiments may only involve a micron of separation from a center-of-mass or "sitting" frame of reference. This view is compared to a lab-frame in which the wave separations might be centimeters of traveling length long.

"X" includes particle properties like mass=frequency=rest-energy, spin, magnetic moments, and electric charge. An electron is an "excitation" of an electron quantum field. A molecule has a description of its atoms and bonds and excitations. In particular, we usually think of charge as being "point-like" and centered in a "particle." But, charge and particle locations are in a weighted superposition of possibilities thus producing a "fuzzy" existence size for X. Is this size the same as the size of D? {the concepts of "size" and "location" are classical – but assume relevance anyway for now}.

"Ψ" represents all encompassing knowledge of states and outcomes and includes wave-function solutions to the Schrodinger equation, $\psi(x,t,s_z) \in \Psi_{\text{ensemble}}$.

A sitting de Broglie frequency tone $f_o \simeq m_o c^2/h$ depends on mass which is a property of X and shared in common, i.e., $m \simeq f \in X \cap D$}. How do the "effective sizes" of D and X compare? Small particles as field-disturbances have imprecise "fuzzy" spatial positions. Again, the clearest example of the need for superposition of locations may be the Aharonov-Bohm "AB" effect for double slit interference. A full particle charge e is needed by both slit-rays for $e\vec{\mathbf{A}}$ adding to and subtracting from particle momentum **p**=mV resulting in a shift in fringe locations. The example of a charged-wire electron beam splitter also requires the presence of electron charge on both sides of the wire for the repulsive splitting of paths even when only one electron is present in a beam. There are other examples such as neutron magnetic moments and spin seeming to be in multiple separate paths [Lemmel].

Particle spin is a property or attribute, "s" ∈ X, but the specific references "up" and "down" relate to the final "measurement" apparatus, M (e.g., $\hat{n}$ orientation of a Stern-Gerlach ∇B_n field gradient) – so we might also have to include preparations and apparatus observation too (context). Ψ can include a Pauli "spinor," χ , for QM {or both spin and energy/momentum together in QFT Dirac spinors}. So, Ψ represents knowledge of both X and D together somewhat as "knowledge" of spin plus energy-momentum over space-time {X∪D ⊂ Ψ } -- subset notation is used because ψ may represent an ensemble of many specific de Broglie waves and more complete broader knowledge. The existence of an electron with its charge automatically couples it to the electromagnetic quantum field. Electromagnetism ($\phi,\vec{A}$) may be included in an electron Hamiltonian as ($\vec{p} \pm e\vec{A}$), and this affects the calculated ψ(x,t) function. "Wave-particle" duality is a feature of D ∪ X.

De Broglie p=h/λ relation for all particles: {relativistic, non-relativistic, and light}

Albert Einstein made the earliest claim that photons of light had energy E = hf and later-on also momentum, **p = h/λ** (= hf/c=E/c, 1908 & 1916). This claim was then verified by the Compton effect experiment of 1923. In 1924, de Broglie proposed that this equation also applies for material particles as well: plane waves accompany matter in relative motion and have wavelength λ = h/mV = h/p. This "de Broglie relation" in turn results from Lorentz transformations of matter rest-mass-frequency $f = mc^2/h$; so, these primal waves represent momentum and energy for all material particles. The early focus of quantum mechanics was on the behavior of electron matter waves. But, fermion rest mass is proportional to the value of the Higgs potential field along with its particular couplings to the various fermion quantum fields with mass originating in a radial vibration in the Higgs potential. Since electrons are excitations of electron fields, the excitation also inherits attributes of charge, spin, special fermion number, a degree of localization and a responsiveness to their environment such as electromagnetic potentials. That information is distinct from just energy/momentum. So maybe excitations are "clouds" of size possibly different from dB "vibration clouds."

With some reservations, de Broglie waves, noted here as "$\delta_{dB}(x,t)$" ∈ D, seem to have some similar behavior to conventional Schrodinger wave-functions, ψ(x,t). Can we begin thinking about primitive dB waves and slowly build up the needs for a transition towards the ψ waves of current quantum mechanics? And do we still have the right to try to picture these objects as embedded in space-time when they have "fuzzy" locations and may also have entanglements?

This present note is mainly concerned with the matter-waves representing "one-at-a-time" particle streams (which includes things like a stream of attenuated and velocity selected buckyballs). It is hoped that reconsidering primitive basics will shed light on the many present-day confusions about the interpretations of quantum mechanics. Multi-particle quantum mechanics is much more interesting and much more complex but will only be touched upon here {Part B, Later}.

A representative example of the interpretations puzzle {"reality" versus "our knowledge"} is the math for the smearing-out elongation of an electron wave-packet over distance and time, Ψ(x,t) with $(x,t)>(x_o,t_o)$. If there is a single electron existing in the packet, is its "actual" space-time presence also smeared out; or does Ψ merely reflect our uncertainties and beliefs about its probable location and momentum among many other evolving possibilities? One of Einsteins views of ψ is that it represented a "statistical ensemble of identically prepared systems" and is hence an "abstract statistical function." Then each individual particle-portion may be more localized in space-time than its overall conventional and probabilistic wave-function. That is, $\delta(x,t)_{dB} \in \Psi_{ensemble}$. Quantum observations are inherently statistical (a processing of data of consolidated events). And the Heisenberg Uncertainty Principle (HUP) uses a commutator based on ensembles of measurements. But, despite that, Niels Bohr famously insisted that the wave function exhaustively refers to a single individual quantum system. Hence, the unpleasantness of "Schrodinger's Cat" and state vector collapse.

A second case of interest is fractional scattering of a plane wave (in the z-direction) off-of a localized central potential with resulting wave-function $\psi(\theta,\phi, k) \simeq e^{ikz} + f(\theta,\phi)e^{ik\cdot r}/ r$ [e.g., Cambridge]. The view of the "Copenhagen Interpretation" is that each detected event is a particular "collapse" of the encompassing spread-out wave function, ψ . It would be conceptually simpler to say that the outgoing spherical wave "really" represents an ensemble of many possible directed plane-wave rays or "wavicles." Quantum mechanics depends on "squaring" quantum probability-amplitudes; so a final scattering distribution might be $d\sigma/d\Omega \propto |f|^2$. For Rutherford scattering, the classical and quantum distributions are the same. A similar example is Einstein's earliest thought experiment of an electron through a tiny aperture with a resulting semi-spherical ψ wave. Does it represent the single particle or an ensemble of de Broglie waves?

To help sort out the essence of the ψ wave-function, consider the simpler and more picturable early concept of de Broglie waves from the 1924-1926 birth of quantum theory. See if beginning with these concepts and then building up from this can be made to function the way we know quantum mechanics does. de Broglie said that every little relatively moving mass possesses a wave behavior with wavelength $\lambda = h/p = h/mV$. It must be emphasized that $\lambda = \lambda(V)$ – depending on <u>relative</u> motion between a "particle" and a frame of reference.

For a better picture, suggest again that free D and X have "sizes." Consider a free δ(x,t) as a spherical *cloud of matter <u>presence</u>* possibly enveloping an actual particle near its fuzzy center **{e.g., $\rho(r) \propto \exp(-\alpha r^2)$ – a "Bell" profile}.** It is likely that this assertion might currently be considered naïve, so I will use the term "toy model" or **"dB-wavicle"** $\delta(x,t) \rightarrow W(x,t)$ -- – a wave-particle simultaneously having the "effective" properties of a wave and a particle together. The "wave" phase part may be expressed as $e^{i\phi} = \exp[i(k\cdot x-\omega t)]$ using "k" for 2π/λ and frequency as ω = 2πf. Could it be that the localized vibration frequency, f or ω, of a "particle" is functionally the same thing as its collective mass? That is, the inertia of a particle **<u>is</u>** equivalent to its localized mass-energy as $f=mc^2/h$. The Schrodinger ψ expresses this phase-wave along with a possible wave-packet envelope and a spinor $\chi=({}^{a}{}_{b})$ for degree of spin up or spin down. The whole wave is a solution of the energy operator equation $\hat{H}\psi = i\hbar\, \partial\psi/\partial t$ where Hamiltonian H expresses linear kinetic energy, angular momentum energy, and potential fields {some of which may be encountered in the future}.

Again, to hope to agree with reality (such as being able to encompass two separate slits at once-- see test values in list), the size of the "dB cloud" would have to be about 1-10 microns or more (*that is, bacterial size*). Is that an "intrinsic" free particle size, or is it due to experiment collimations? Suggest that an accompanying particle nature also has a "size" due to a cloud of position locations perhaps caused by fluctuations or intrinsic "fuzziness" in space-time.

A single electron at rest is represented by a unique de-Broglie '**<u>tone</u>**,' $f=mc^2/h$ as a **zeta-hertz** nonpropagating wave having the same instantaneous phase everywhere. By applying a Lorentz transformation for relative motions, tone vibration can also be seen as a moving dB-wave obeying

$\lambda = h/p$. [see **Appendix** below for math]. Besides representing pure matter-energy, an electron "mass-vibration" tone is a quanta of excitation of its pervasive "electron field" and should inherit electron properties such as charge, spin, conserved electron fermion number, and a degree of localization.

*{Note that text-book Copenhagen disagrees: "de Broglie waves, also known as matter waves, do not carry charge. de Broglie waves are **probability waves** that only carry information about the likelihood of finding a particle in a specific place and time. They do not have mass, charge, energy, momentum, angular momentum, or any other physical quantity." Physical systems generally do not have definite properties prior to being measured}.*

In contrast, I wish to consider here that a "cloud of existence or presence" associated with the "tone" does contain some "cloudy" attributes of charge, spin, and total energy represented by vibration. And I want to picture this in space-time. The momentum attribute is represented by wavelength due to relative motion. Angular momentum is an orbital standing wave. There is a rule that dB waves "have a desire to reinforce themselves repeatedly" via constructive wave interference into linear or orbital standing waves constrained by KE and PE energy requirements (e.g., radial Coulomb potential). That's the claim for circular Bohr orbits with integer actions {and, although they may represent reality poorly in 3D, they are relevant in 2D surface film cases such as the integer quantum Hall effect}. Stationary wave constructive interference is a property of the wave function. When there are standing waves, the cloud of presence has electrical charge delocalized into $\rho_{charge} = e\psi^*\psi$ – an old idea that is sometimes dismissed but is also a central concept of density functional theory (DFT) in solid-state and molecular physics. Rather than being instantaneously true; given the peta-hertz rapidity of an "orbit," it could just be "effectively true" – an effective smearing out. It also means that the "cloud of presence" is malleable – when bound, it need no longer form into a spherical shape.

A crucial test of this "spherical cloud of presence" model is ability to diffract through a double-slit mask [Tavabi]. When these huge clouds encounter the mask barrier, most will be reflected back or absorbed. Only two small rays of the vibration disturbance will make it through the two small slits. The multi-micron size of the oncoming cloud accounts for the cases listed in the experimental values list. But the cloud may then be broken up (forcing it to have an apparent behavior of a ψ-amplitude – a weighted superposition of ray amplitudes). The splitting of de Broglie waves into two "beams" would appear to be a "show stopper" – and it might well be. On the other hand, even for a single particle, being able to go forward-and-backward-in-time enables two split matter rays to still be connected via their original single being. Perhaps that is the only way to make sense of widely separated paths in grating interferometry or "Mach-Zehnder interferometry" (e.g., centimeters of separated path lengths). There may be a holistic interconnectedness in space-time where time needn't progress only forwards. If we consider this splitting from the center-of-mass view, then useful experimental separations are much smaller – perhaps only a micron or so.

As mentioned before, a clearer example is the splitting of a tone in its own frame of reference by a thin wire with negative potential. The tone splits into two separating parts, but the particle properties of each part are **not diminished in proportion** – they remain full strength but in spatial superposition. In particular, the interaction of each part with another electrostatic or vector potential is $e\phi$ or $e\vec{A}$ with full charge e in both parts. This is consistent with the path integral view where a "particle" takes all possible paths experiencing various potentials along the way, and then all paths are considered as superimposed and interfering as a group.

One primary question is, "Is the particle mass the cause and center of the vibrating cloud?" It is one holistic package in which the cloud vibration represents the electron mass-energy. It is hard to probe much deeper because the origin of particle mass after electroweak symmetry breaking is not yet perfectly understood. Rest-mass/energy/frequency is Nature's Universal way of coding energy; and when in motion—momentum. The wave by itself says nothing at all about the details of the particle beyond energy and momentum.

There are several views and choices about what happens next:

Copenhagen would say the wave-function has waves of probability amplitude going through both slits and that the "particle" only becomes truly localized in space upon wavefunction collapse during interaction with a classical detector (e.g., a detector screen or CCD). A particle "could" have gone through either slit, so those possibilities have to be weighed in a superposition of amplitudes.

Another view is that the particle actually goes through one of the slits, and the transmitted rays from both slits are guiding-pilot waves that guide the particle towards its interference maxima (a de Broglie-Bohm view, "dBB" [Towler]). There is then no need for collapse because "the particle is already there." For the "AB" effect, the guiding wave has nonlocally included the existence of a rotating vector potential field, A(x,y,z).

The de Broglie cloud and (possibly existing material) particle must be synergistic (e.g., perhaps like de Broglie's double solution – although, after a century, that is still not well-developed). If a spherical cloud tone is produced by a massive particle; then after the contortions of passing through a small slit, the free ray should re-constitute into its big cloud. But most of it is so spread out that it might not contribute more to maxima than the original rays. Actual experimental interference maxima are well balanced with decent visibility.

The "Sum over Histories" view is that there is a particle with a wavelength that actually takes all possible pathways, and then a path integral sums up the amplitudes for a probability interference profile. A single particle goes through both slits and everywhere else too. So too do all the Huygen's wavelets.

A field theory view is that there are only quantum-fields and that an output "particle" is a deduction based on final localization in space and time as a detector event. "Both 'particles' and 'waves' are merely two ways in which we naively interpret excited quantum fields." It is hard to see how this view can apply to buckyball-C_{60}-molecules. It might make more sense to simply say that free particle locations are fuzzy at a microlevel.

The field view concept works well most of the time for photons in quantum optics and possibly for electrons as elementary particle excitations. In-between emission and detection, a "photon" is often called just "a wave of probability." But it is much harder to believe this ethereal view for big C_{60} buckyball molecules which are highly composite and much more particle-like with innumerable rotational and vibrational spectra {and see **Fig. 1b** for an atomic microscope photo, **AFM**}. They do have de Broglie wavelengths and do make interference patterns after a double slit. But, it is very hard to think of them as just fields and certainly not as just waves. This single observation pushes one towards a dBB interpretation. Most physicists accept that particles have "fuzzy" space-time

If an electron beam goes through a tiny hole where $\lambda \sim$ diameter d, diffraction spreads out the beam. Each portion of that beam has its own $\delta(x,t)$'s disturbance of the energy field {note that single-hole or single-slit electron diffraction tests are very difficult to actually perform and so far only show minimal bending of output rays – see Appendix at end}. Similarly, when electron-beam crystal-diffraction produces interference spots, each spot contained its own $\delta(x,t)$'s.

"dB-Tones"

It seems very strange that few physicists seem to be aware of de Broglie's foundational nonpropagating frequency-cloud "tones" and that Lorentz transformations of these vibrations yield $p = h/\lambda$. This de Broglie relation is usually treated as just a given rule lying below the usual postulates of quantum mechanics. Could re-focusing on this provide a new view into quantum reality and quantum nonlocality towards making a decision towards a better story of quantum mechanics?

de Broglie began by taking $E = h\nu$ seriously for massive particles as well as photons and from that derived $p = h/\lambda$ via a Lorentz transformation to a relatively moving frame of reference. For electrons, $\nu_e = mc^2/h \sim 1.2\times 10^{20}$ Hz (0.12 zeta-hertz!) is a rapid pulsation that perhaps could be labeled as a pure **dB-tone**. He supposed these tones to have the same phase at a distance at any given time, t. "In the "intrinsic" system of the corpuscle in the sense of the relativity theory, the wave will be **stationary** since the corpuscle is immobile: its phase will be the same at every point" [Nobel 1929][Schuler]. That is, "a point of constant phase on the De Broglie wave is a point of simultaneity in the reference frame of the particle." A dB-cloud of presence is vibrating. That means that a sitting "tone" by itself is non-local and holistic with an occasionally applied label of being "beyond space-time." The phrase "being in space-time" means Minkowski space-time, honoring Lorentz invariance, and not allowing superluminal communications. That is already broken for Ψ on configuration space with multiple spatial coordinates.

It is difficult to picture an electron-sitting-vibration because it is going + to – amplitude of presence in 3-dimensions – and we don't know how it attenuates in space or even if it does localize in space. For convenience, suppose it has a Gaussian 3d shape. We could at least picture it in two of its dimensions versus time. That is similar to the case of the hydrogen ground state S-orbital vibration: imagine a 2-d rubber sheet that is poked up by a tent pole (that particular shape is due to a having a central attractive potential from the proton). Then the tent pole falls and goes negative below the sheet and then back up to + again. The hydrogen ground state has $E_{kinetic} = -\frac{1}{2} V_{electrostatic}$, so energy E = =KE + PE = KE-2KE = -KE = -13.6 eV ionization energy (energy needed to free the bound electron). Its frequency is $\nu = cE_k/(hc=12.4 \text{ keV}\cdot\text{Angstroms}) = 3.29$ PHz (peta-hertz, 10^{15} Hz!). It's an interesting number because we are now able to observe chemical changes using femto-second laser pulses – the same period range. For the sitting electron, instead of a pointy tent-pole, we imagine pushing up the rubber sheet with a broad spherical shaped cap (-- up + then down – repeat). It is also interesting that there are two functional frequencies for the S-orbital electron: the non-relativistic kinetic-energy PHz value and the QFT-mass-relativistic ZHz value – 5 orders of magnitude higher. The de Broglie wavelength derives from the zeta-hertz frequency, but textbook (non-relativistic) quantum mechanics use the peta-hertz range of frequencies.

The uncertainty principle of quantum mechanics is simply a Fourier-algebra property of any system described by waves [Mead]. Applied to this case, **if** a $\delta(x)_{V=0}$ "tone" is indeed in spacetime and has a gaussian envelope, its Fourier transform (also a gaussian) might be meaningful. $\sigma_x\sigma_k = \frac{1}{2}$, so $\sigma_k = 1/2\sigma_x$. If $\sigma_x \sim 1$ micron, $\sigma_k \sim \frac{1}{2}$ microns. $p=\hbar k$, so $\sigma_p \sim h/4\pi(1\mu\text{m})$ or $pc \sim hc/4\pi\ (1\mu\text{m}) \sim$ 12.4keV(angstroms)/4π 10^4 angstroms ~ 0.1 eV. (perhaps compare to electron rest energy 511 keV).

de Broglie-Bohm theory {dBB} has not gone away and is still being actively developed. Some authors say "Bohmian mechanics is not just a counter-example to some orthodox claims, it is the most serious theory of quantum mechanics that we have" {[Tumulka] and a series of DGZ author papers}. "With a simple shift of perspective, QM can be reformulated as a dynamical theory of particle trajectories rather than as a statistical theory of observation" [forum]. "One of the main problems remaining for the Bohmian (or any other) approach is to find a satisfactory relativistic quantum theory, a theory that is fully Lorentz invariant while avoiding the profound conceptual difficulties of orthodox quantum theory. There are actually a multitude of attempts in this direction – just a lack of consensus. When looking for a relativistic extension of nonrelativistic Bohmian mechanics one inevitably encounters two central, very different problems: that such an extension must involve a **mechanism** for nonlocal interactions between the particles, and that quantum equilibrium cannot hold in all Lorentz frames. For both of these problems the additional space-time structure provided by a foliation yields the most obvious solution" [DGZ]. But, Bohmians are not considering the transactional {back-and-forth-in-time} interpretation which can avoid this.

Electron Beams:

An electron dB-wave going through a double-slit test may encounter slit separations of 500 nm (sideways to particle motion); then successful interference experiments demonstrate electron beam "spatial coherence." Interference fringes are only observed as a big statistical ensemble of many de Broglie waves each forming single dots on a detector screen. Phase coherence can mean a fixed phase relation perpendicular to travel direction (i.e., encompassing all grating slits). Each dB-wave has internal coherence, but group coherence depends also on all particles having nearly the same energy (chromatic) and coming from a small source. Electrons generated at a good electron gun assembly will have nearly the same energy. But any variation in energies means a variation in momentum and wavelengths which can form a collective ensemble wave-packet. Along the direction of the electron beam, having a good "temporal coherence length" is determined by the monochromaticity of the beam. "Sub-nanometer and nanometer-sized tips provide high coherence electron sources" [zora][joel].

Some particular experimental test value examples (added on the previous list) include:

Electron beam energy E =250 eV with a small $\Delta = 0.1$ eV spread can give a temporal coherence of $\ell \simeq 390$ nm. The longitudinal coherence length of a scanning electron microscope (SEM) at 25 kV can have a record longitudinal coherence length of 690 nm. For a 200 keV transmission TEM with beam diameters ranging from 2.0–6.9 µm, one might see a transverse coherence length of 7-19 nm and a longitudinal coherence length of 2.5 nm. The numbers vary but lie between nanometers to below a micron. Like the case for light, transverse coherence (perpendicular to the direction of propagation) can be increased by collimation.

Matter waves can also participate in Mach-Zehnder type interference experiments using electrons or neutrons and soon Helium atoms. For neutrons, perfect Si-crystal neutron interferometry is equivalent to a Mach-Zehnder interferometer. One example has path lengths near 10 cm and slow neutron wavelengths $\lambda \sim 1.9$-4.4 angstroms [Rauch].

It has been claimed that the neutron's interaction with matter is {counter-intuitively} dominated by the strong force neutron-wave-on-nuclei interaction leading to Bragg scattering; and there is also a spinor portion to the neutron wave function with 4π symmetry {1975, Rauch}.

For electron beams, one MZ test using gratings had an MZ path length near 5 cm using 6-10 keV electrons [Gronniger].

The collective wave-function for an electron beam may look like shape-modified plane-waves: **Ψ(r,z,t)** = **J**(r, k_r) exp(i(k_z z – ωt)) , where **J**( ) is a beam radius shape function (e.g., "Bessel beam"), and k is wavenumber in the r or z direction. We could even add orbital angular momentum {vortex OAM} by including a $e^{in\phi}$ term around the cylindrical beam (!).

Supposedly, this isn't a "complete" wave-function because it is lacking all the multi-particle interactions and their configuration space (the set of position coordinates of a system). If we had that Ψ, deBroglie/Bohm would consider it a dBB wavefunction; so Ψ(r,t) and δ_{dBB}(r,t) would be the same. In general, "N noninteracting particles can be described by N wave functions in 3D, but the interaction between particles invariably leads to entanglement between the particles and thus N 3D spaces are not enough to describe the state of N quantum particles" [Vaidman] .

Regarding long range entanglement, few have considered "Time symmetric theories:" They explain entanglement as not being a true physical state but just an illusion created by ignoring a limited form of retrocausality. The point where two particles appear to "become entangled" is simply a point where each particle is being influenced by events that occur to the other particle in the future." [wik]. Outcomes obey conservation laws, but how are they enforced in Nature? Some sort of sub-quantum relating agreements between sources and outcomes could resolve this.

Conclusions:

After a century of debate, it is appalling that the physics community still hasn't come to any agreement on the meaning of quantum mechanics. I'm very impatient for a decision and wish to convince myself of a likely interpretation. There are three somewhat new awarenesses that might help.

1. A most primitive starting point should be that p = h/λ is derived from a particle's sitting frequency f = mc^2/h (a fact not often stated nor appreciated). It is interesting that the de Broglie relation also works well for ordinary quantum mechanics in which energy is simply kinetic and potential, and rest mass-energy is ignored. Waves are real in quantumland.
2. Another awareness is that large molecules also demonstrate this relation and show 2-slit interferences. A C_{60} "buckyball" is a complex particle. An intuitive belief is that it must finally go through only one slit while its dB-wave goes through both and interferes with itself. Since a dB-wave is only intended to represent energy and momentum, it makes little sense to believe that it travels as a wave and upon detection "collapses" or re-constitutes and materializes as a particle. But, if we accept that, then, Why should electrons be different? Apparently, spatial localization of particles is hard.

Copenhagen says the particle travels through both slits as a superposition state of the two possibilities. It is the wave that explores those possibilities and forms interferences. We needn't say the "particle" goes through both. We are continually hung up on what we have called "wave-particle duality." Feynman's alternative trajectories essentially explore a multitude of Huygen's wavelets—which is what a wave does. We say that Feynman started out as a "particle guy" but may have ended up as a waves or fields guy. Rodney Brooks said, "There are no particles, there are only fields."

3. In general, "**How are conservation laws enforced in quantum mechanics?**" They begin as a state expressing a superposition of alternatives, and then a final resolution between parts {a superposition in amplitude space leading to classical answer}. Something "resembling" the transactional interpretation seems to be required where originating events and detection events are inter-related and perhaps

iterated until they agree with the various conservation requirements imposed by Nature. This is an essential ingredient in the workings of "entanglements."

Changing my views about Quantum Mechanics?

I'm now more willing to accept that quantum **mechanics does explore all possibilities prior** to a final decision or "collapse." An electron "could" have gone through either slit, so consider the electron in both slit rays as a superposition of amplitudes which can interfere. The splitting of rays may make it unlikely that a real particle is tied to a de Broglie wave presence unless "retrocausality" is present.

I'm still thinking that "randomness" in probability might be only an apparent result of a hidden "final selection mechanism." One idea is that source and detection have to have matching phases – and phase is random between [0 and 2π). This has been shown concretely by Mead for the Wheeler-Feynman interpretation of electromagnetic rays between source and detector.

On the major features of quantum mechanics: wave-particle duality (tricky subject), probability amplitudes ("quantumland" is a sub-reality), superpositions of amplitudes, the Born rule (might be explained by the two parts of a "transaction" or by Bohm quantum equilibrium), and unitary development followed by purely random collapses (Einstein didn't believe in randomness- - there might be a hidden event selection mechanism such as phase matching).

The psychology of major contributors and the complex sociology of the physics community have been players in the interpretation debates. Despite very intelligent people advocating many "far-out" ideas, it seems safe to me to ignore extraneous factors such as the consciousness of an observer, connections to a "wave-function of the universe," branchings into a multiverse, and also "instantaneous collapses" of a wave function.

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Appendix Topics:

- Single-slit electron diffraction
- de Broglie "Tone" to Wave Math
- Counting de Broglie waves with Lagrangians
- Jayne's 'Quantum Omelette quote'
- More on Bohmian views
- End Notes
  - Notes on Bell Inequalities
  - More on the Double Slit Experiments
  - More on the de Broglie Relation

Single-slit electron diffraction.

It is extremely difficult to produce slits smaller than a micron in size. For visible light, to get say a 3 degree Δθ bending requires a pinhole of diameter d ~ λ L/Δr. In particular, for green light λ ~ 500 nm; and if L ~ 30 cm to detector screen, then d~ 20λ ~ 10μm hole size. That's achievable.

But, typical electron beam wavelengths are in the 1-50 **pico**-meters range which is about a thousand times smaller so that deflection angles have to be tiny. High quality single slits may require

"FIB" focused-ion-beam milling machining {e.g., on a Si_3N_4 substrate}; and this can also enable better up-front collimators of an incoming electron beam. Electrons are charged, and that introduces extra interactions between a beam and the material of a slit or grating requiring difficult calculations using image charge potentials [e.g., Barwick, 2006]. When that complexity is accounted for, one can then clearly see single slit diffraction such as five resulting downstream peaks that agree with Fraunhofer optical diffraction theory {experimental example: E= 500 eV on a 140 nm wide single slit with distance to detector of L ~ 24 cm.}

Another approach is using solid-state circuit quantum point contacts (QPCs): narrow constrictions between two wide electrically conducting regions with a width comparable to the electronic wavelength (nano- to micrometer). This enables two-dimensional electron gas flow and a "first comprehensive demonstration of electron diffraction in QPCs" [Khatua, 2014].

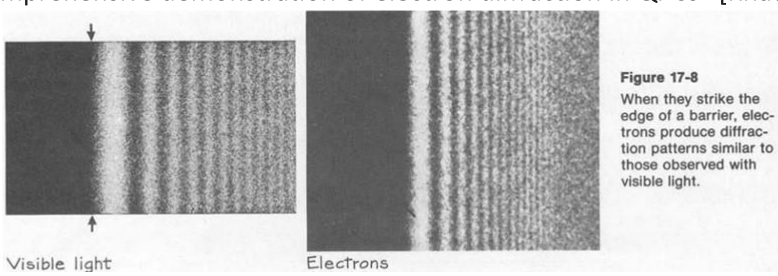

Figure 17-8
When they strike the edge of a barrier, electrons produce diffraction patterns similar to those observed with visible light.

Figure : For the case of single edge diffraction, the patterns are similar for visible light versus electron waves (on MnO substrate).*: Ref: https://web.phys.ksu.edu/fascination/Chapter17.pdf*

de Broglie tone to wave Math:

The "Compton frequency" $f_C = mc^2/h$, or $\omega_C = 2\pi f_C = mc^2/(h/2\pi) = mc^2/\hbar$ [1923, with a convention of using "rest mass," $m = m_o$, rather than relativistic γm_o].

There is also a "Compton wavelength" $\lambda_C = h/mc$ (so the product $f_C\lambda_C = c$!– like for a γ-photon with an electron's mass-energy. For relativistic matter waves, we would instead have $f\cdot\lambda = v_{phase} = c^2/v_{group} = c^2/V$). The wave-number 4-vector $K = (\omega_C/c, \mathbf{k})$.

The Lorentz transformation of a 'pure ω_C' rest frequency (where initial $\vec{k} = 0$), yields $\mathbf{k' = \pm \beta\gamma\omega_C/c}$,

So, $2\pi/\lambda' = V\gamma 2\pi f_C/c^2 = 2\pi V mc^2/hc^2$, or $\lambda' = \lambda_{dBroglie} = h/\gamma m_o V$ **= h/p.** (the standard relation). Also, $\lambda_C \simeq \lambda_{dB}(V/c)$.

In non-relativistic quantum mechanics, the de Broglie relation is usually just a given along with E = hf. But p = h/λ is derived via a relativistic Lorentz transformation for a moving reference frame beginning with the more primitive E = hf relation.

Counting de Broglie Waves via Lagrangians for non-relativistic Schrodinger Quantum Mechanics {NRQM} versus Special Relativistic quantum mechanics {RQM}:

In the realm of quantum mechanics, the Lagrangian $\mathbf{L_{QM} = KE - PE = T\text{-}V = \frac{1}{2} mv^2 - V}$ and relativistic $\mathbf{L_{RQM} = -m_o c^2/\gamma - V}$ where "action" $S \equiv \int L\, dt$. These Lagrangians are essentially counters for the number of de Broglie waves along a path [ref. "Learn," dp]. They are very useful in determining equations of motion via "least action" Euler-Lagrange equations [1755-1766] or Feynman Path Integrals {"Sum over Histories"}. The math showing this is short and simple but not quite intuitive because the formula for L_{RQM} looks implausibly different from that of NRQM or for use in Newtonian mechanics.

For simple understanding, we would like to picture the de Broglie waves as a fixed **[δ_{dB}(x,t) <u>Sine wave drawn on cardboard</u>]→** in relative motion traveling in space-time. This represents "Phase Waves" of velocity $v_\phi = f\cdot\lambda_{dB} = \omega/k$ passing through an envelope of a wave packet with center moving at a group velocity, v_g. If ω as a function of k is found, then $v_g = \partial\omega(k)/\partial k = \partial T/\partial p = 2p/2m = mV/m = V$. *We see something like this in a stone 'ker-plunk' in a pond where many little consecutive circular ripples pass quickly through radially outgoing broad water waves.*

For the simpler case of electro-magnetic waves, the phase speed and group speed are the same—the speed of light c. So, the sine wave on cardboard moves at the speed of light which is also the speed of the "photon." This is an idealistic picture of course, real material cardboard couldn't do that. But it can in our imaginations.

Going back in history, the old "**action** of Maupertuis" [1744-1751] was essentially S =∫ vdx" or "∫ pdx" using momentum p = mv. This can be rewritten in terms of time as:

dS = Ldt = pdx = $mvdx = m(dx/dt)dx = m(dx/dt)dx(dt/dt) = m(dx/dt)^2dt = mv^2dt = 2(KE)dt =$ **2T dt.**

{Least action works for any flexible $S = \int L'\,dt$ <u>for **L' = aL + b** as a re-expression</u>; so L' = 2·KE is ok for free particles}.

Quantum "phase" in radians is $\phi = (kx - \omega t) = (px - Et)/\hbar$ where E= T+V. Then wave counts are:

$n = \Delta\phi/2\pi = (1/2\pi)(p\Delta x - E\Delta t)/\hbar = (2T - (T+V))\Delta t/h = (T-V)\Delta t/h = L\,\Delta t/h$. {this is also a simple derivation of the non-relativistic Lagrangian <u>as **L = T-V**</u> in units of h}.

Now, for the free particle case of $E = T = p^2/2m$, $v_g = \partial E/\partial p = p/m = v$ {particle speed}. And, $v_\phi = \omega/k = E/p = p/2m = v_g/2$. So, relative to an observer moving at particle speed, the phase speed is going **backwards**. The cardboard sine wave is moving opposite to particle motion. That is standard lore in textbook QM, but it uses the "peta-hertz" vibration rather than the relativistic "zeta-hertz" vibration.

So, $\Delta n = \Delta\phi/2\pi = (\Delta x/\lambda\Delta t - f)\Delta t = (v_g - v_\phi)\Delta t/\lambda = ½\, v_g\,\Delta t/\lambda$

Or number of λ wavelengths is $(v_g/2\lambda)(t_2 - t_1)$.

For the **relativistic** case:

$n = \Delta\phi/2\pi = (p\Delta x - E\Delta t)/h = (\gamma mv\Delta x - \gamma mc^2\Delta t - V\Delta t)/h = [-\gamma mc^2\Delta t(1-v^2/c^2) - V\Delta t]/h = -mc^2\Delta t/\gamma h - V\Delta t/h$

And least action $\delta S = \delta\int L\,dt = 0$ where $\mathbf{S = -mc^2\int dt/\gamma}$ $- \int V dt$ from t_1 to t_2.

Again, L' = aL + b is also an acceptable Lagrangian; and let a = h. We often set $c = \hbar = 1$ anyway.

For v_{group} use $E = \sqrt{[(pc)^2 + (mc^2)^2]}$, and $\partial\omega/\partial k = \partial E/\partial p = pc^2/E = (mv)/m = v = v_{group}$.

Also, $v_\phi = \omega/k = E/p = \gamma mc2/\gamma mv = c^2$, or $\mathbf{v_\phi v_g = c^2}$ **and** $\mathbf{v_\phi > c.}$

Again, $n = \Delta\phi/2\pi = (p\Delta x - E\Delta t)/h = (\Delta x/\lambda\Delta t - f_{rel})\Delta t = (v_g - c^2/v_g)\Delta t/\lambda = v_g\Delta t(1-(c/v_g)^2)/\lambda$

{appears to have rapid wave train motion opposite to the direction of travel} – a bit of a puzzle. Mike Jones points out that $v_\phi = c^2/v_g$ is scalar and doesn't refer to signs. The phase wave could go in the same direction as the group velocity. }

The imaginary cardboard sine wave zips along faster than the speed of light.

There is an <u>alternative</u> to treating Lagrangians as phase counters and physics as phase interference in the principle of least action.

For gravitational physics, a somewhat different fundamental rule suffices: **the "principle of extremal proper time"** which yields geodesic particle paths through spacetime. In the Newtonian gravity approximation, this agrees with the standard classical Lagrangian, **L = T-V** = kinetic energy minus potential energy; i.e., $d\tau/dt = 1+(V-T)/mc^2 = 1- L/mc^2$. The combination of Lagrangian with accompanying "Euler-Lagrange equations" {"EL"} is traditionally justified as being an alternative but broader formulation of Newton's laws and results in familiar equations of motion.

It is claimed that a deeper understanding of Lagrangian "Least-Action" depends on **knowing the underlying mechanisms that enable conservation laws to be enforced by Nature** {"**reconciling**" inputs and outputs}. This is also associated with the concepts of "collapse of the wavefunction" and "particle entanglement" correlations. The future development of something equivalent to the transactional interpretation of quantum mechanics would be helpful.

[**Jaynes**]

A major statement of the interpretations problem was given by Jaynes: **"Unscramble the Quantum Omelette":**

"But our present QM formalism is not purely epistemological; it is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature {all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble. Yet we think that the unscrambling is a prerequisite for any further advance in basic physical theory. For, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about; it is just that simple. So, we want to speculate on the proper tools to do this." {… and later adds: "the resolution cannot be found within the confines of the traditional thinking of physicists."}.

More on Bohmian Views:

As an initial thought, consider "placing" a sitting-tone in a long thin rectangular potential box with "thin" length "L" in the x-direction. How can quantum standing sine-wave shapes be produced for this case? Here there is no moving observer; but in canonical QM, something will make the electron vibrate in the x-direction.

The imposed boundary surrounding the tone would try to truncate the shape. We may desire the unaltered shape to have some natural intrinsic degree of localization that we can picture in space-time (perhaps a micron or more but not infinite). A gradually attenuated profile could include things like "Gaussian" ("bell") shapes or raised cosine curves $(1+\cos(r\pi/\alpha))$ – but long exponential tails might be more reasonable (and dovetail better with QFT). For comparison, the ground state of a spherical harmonic quantum oscillator is an example of a bell shape: $\varphi(r) \propto \exp(-\alpha r^2)$.

Suppose all parts of the "tone" are capable of interaction (mainly from external electric charges and potentials). Suppose the electron charge is indeed distributed as a cloud within the shape curve (e.g., $\rho = e\psi^*\psi$ {but, the combination $\psi^*\psi$ brings ψ into the classical realm}) . Obtaining a standing wave inside the boundary requires that the "sitting tone" evolve some momenta; and the traditional source might be the usual uncertainty relation $\sigma_p > \hbar/2\sigma_x$. That in turn means that Fourier transforms are useful for describing tones (within space-time). And that means that the de Broglie tones and waves already have resemblance to usual ψ-wave quantum mechanics; but the probability interpretation is not yet apparent.

The "Bohmian" view of this is that any resulting energy change $\{\Delta KE = p_x^2/2m\}$ is absorbed into a **"quantum potential" Q** = $(h\backslash k_x)^2/2m$ with $k=n\pi/L$. The "particle" is still at rest unless one potential boundary wall is removed. Then the stored up Q goes into "real" KE of new motion.

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Notes:

The 'g' in **de Broglie** is silent, so **his** name is pronounced 'the Broy' to rhyme **with** 'toy'

Double Slit Experiment:

In water ripple-tank demonstrations with plane waves on double slits, the rays from the two slits can superimpose and interfere. They are excitations on the surface of the same water medium. For electron experiments, electrons are excitations of underlying universal electron fields that exist everywhere before and after the slit barrier. Their waves are due to mass and velocity that belong to the inertial frames of spacetime; and the two electron de Broglie rays have the same wavelengths and propagate at the same speeds. The field medium may be similar to the case of water medium.

For an analogous situation for photons: Suppose a plane barrier lies in a z-direction and EM-waves propagate in an x-direction. Moving or sitting charges are the sources of electromagnetic fields. Let a z-oriented vibrating electron dipole radiate in the x-direction towards double slits, $A_z(x,t)\hat{x}$. The underlying EM quantum field exists on both slides of the slits, so the approximate plane wave rays are of the same medium and can interfere.

`The existence of sitting or moving charges is the source of excitations the quantum field representing electromagnetism (“EM”); so, a combination of both charge and mass in electrons inter-relates the electron-field and the EM-quantum-field. One result of the blending of these two worlds is the Aharonov-Bohm (AB) effect showing that vector potentials can cause a shifting of peaks in wave interference (quantum phase shifts). This implies that the momentum causing scalar de Broglie waves from $p_{kinetic} \equiv mv$ now also has an additional contribution from “electromagnetic” momentum $e\vec{A}$. That is, for charged particles, “canonical momentum” $p = \hbar\vec{k} = m\vec{v} + e\vec{A}$. This is a conserved quantity, but $\vec{A}$ contributes nothing to energy and is hence subtracted off when writing the “Hamiltonian” $H = |p-eA|^2/2m - e\phi$. The ratio e/m is the same in all parts of a superposition. The electron may have mass in motion v, and electron charge experiences something resembling a “dragging of electromagnetic space” by currents such as $\vec{\mathbf{J}} \propto e\vec{\mathbf{v}}$. The magnetic vector potential of a moving point charge, $\vec{\mathbf{A}}(r)_{MKSA}=\mu_o e\vec{\mathbf{v}}/4\pi r$ falls off with distance from the charge and is the result of a Lorentz transformation of Coulomb fields.

[Arndt] https://www.researchgate.net/publication/251170703_Wave-particle_duality_of_C60_molecules "Of particular interest is the fact that C_{60} is **almost a classical body, because of its complexity and its many excited internal degrees of freedom** and their possible couplings to the environment. Such couplings are essential for the appearance of decoherence suggesting that interference experiments with large molecules should facilitate detailed studies of this process… , C_{60} fullerenes (Dynamic Enterprises Ltd, Twyford, UK) which were sublimated in an oven at temperatures between 900 and1,000 K. The emerging molecular beam passed through two collimation slits, each about 10 mm wide, separated by a distance of 1.04 m. Then it traversed a free-standing nanofabricated SiNx grating consisting of nominally 50-nm-wide slits with a 100-nm period.

Note: In an atomic orbital, in addition to θ,ϕ parts of wave functions, there are also radial functions that constrain electron presence into narrow radial bands (eψ*ψ at the Angstrom level well below the micron size level). Deviations too far outside these constraints lead to an imbalance of kinetic energy with respect to potential energy V(r) – and that is not allowed.

"Presence" has an amplitude that becomes intense in stationary states. This is consistent with total integrated presence being normalized ∫ψ*ψ dVol = 1. So a free particle can have wide presence, but a bound particle can have narrow intense presence.

Rodney Brooks said, "There are no particles, there are only fields."

Special Notes from Zeilinger: For Bose-Einstein wave interferometry, fringe spacing is determined by the mass of individual atoms rather than the collective mass of the condensate (an exception to the rule). For covalently bound assemblies of atoms, it is indeed the total collective mass that counts.

More on the de Broglie Relation:

Note : Chem.libretexts.org (freshman teaching) derives the de Broglie relation "badly" from $E = hf = mc^2$ but then noting that matter must have V < c. So, replace the c with speed: $\lambda f= V$ and $hf = mV^2$, then mV= **p = h/λ** (Yes, but very poor handwaving since relativity says $\lambda f = \omega/k = E/p = mc^2/mV = c^2/V$.) -- It claims de Broglie treated matter waves like light waves.

Now, the Compton effect using "Compton wavelength" $\lambda_c= h/mc$ was published in 1923 – a year or so before de Broglie's hypothesis $\lambda_{matter} = h/mV$. The similarity might have been a motivation for the idea of matter waves, but de Broglie was also well versed in special relativity and could provide more valid derivations. The relation p = h/λ was not just a wild hypothesis. {Actually, de Broglie had a much more advanced model in mind: a double solution of a vibrating soliton surrounded by a psi-cloud also vibrating at the same frequency. This model was never perfected.}

The de Broglie relation p = h/λ also explained Bohr orbits. Here orbital circumference $2\pi r = n\lambda = nh/p$ to get circular standing waves; and $pr = n\hbar$ = Bohr's **action**. {For the first n=1 (ℓ = 1) Bohr orbit at a Bohr radius of a_o=0.53 angstroms, KE = 27 eV (double the S-orbital binding energy) and $f_{KE} \simeq 6.5$ PHz}. This reasoning uses $mVr=nh/2\pi$ for standing waves, so speed $V = h/2\pi m r_o$. E = hf where $f = V/2\pi r_o$. Although a very high value, this is still a non-relativistic frequency rather than $f\simeq \gamma mc^2$. de Broglie was aware of this, but the math switches the original mass energy frequency to the non-relativistic energy which ignores mass-frequency by convention.

Part B for multi-particle Quantum Mechanics. {a few comments}.

Bell's Inequality of 1964 is merely a classical statistical statement using logical Venn diagrams and binary test results. But it is still somewhat challenging to understand and has many different forms for different test cases. It is tricky and not obvious. If it were simple, someone else would have come up with it before Bell.

BELL inequality statement: If [a hidden-variable theory] is local it will not agree with quantum mechanics, and if it agrees with quantum mechanics it will not be local. Bell nonlocality is not signaling causation but rather just an experimental correlation. Two of the common types of entanglements in spacetime are shaped like a **V** and a **W** (with time progressing upwards). The two sides of the V are entangled from a common source at the vertex. "W" begins with two independent "V" vertices at bottom. A "Bell test joint measurement," M, at the center top of W can entangle the outward sides even if they have never previously interacted (entanglement swapping). It is OK for M to occur **after** measuring the sides (delayed choice).

For the simple **V** case, let detectors/experimentalists at top left be called "Alice"= attribute a for ↖ and right "Bob" =b for ↗ with two possible test outcomes for each attribute.
[Wikipedia] discussing the Bell Inequality shows a relevant example called "CHSH" named after four physicists. It has two key "assumptions: first, that the underlying physical properties a_0, a_1, b_0 and b_1 {experimental outcomes} exist independently of being observed or measured (sometimes called the assumption of *realism*); and second, that Alice's choice of action cannot influence Bob's result or vice versa (often called the assumption of *locality*)." The Bell inequality itself is simply a statement of logic rather than quantum mystery. For a List of possible Bell tests see [Bell list].

Bell inequalities for optics are statistics statements about object attributes labeled as A, B, C applied to each of two entangled photons (could call them Left and Right rays). It was Bohm who considered EPR restated as electron spins and then Bohm/Aharonov for photon polarizations. A, B, and C are expressed as areas in Venn logical diagrams where we care about each attribute having a + or – result (binary, or 1 and 0). This is just a math exercise without regards to actual quantum mechanics behaviors. Instead of the usual three big overlapping circles for ABC, we redraw areas and overlaps to emphasize **pairwise** + - for each (two of the ABC choices at a time). And then we test for relevant cases of L and R having the same or different values of 1's and 0's. For spins, ABC might be angles 0, 45, or 90°. For polarizations, we might use ABC angles 0, 30 or 60°. Photons transmitted through a polarizer are 1's and blockage is 0's.

There are many possible Bell inequalities, and we select one that is most appropriate to an actual quantum entanglement correlation test and the form of its Bell entanglement state. For electron spins from a singlet state, one electron with spin up means that the other electron will have an opposite spin down {form $\Psi^- = |10\rangle - |01\rangle$ }. For positronium e^+e^- annihilation, two gamma rays will have mutually orthogonal polarizations – again the form Ψ- but representing optical polarizers vertical and horizontal. For double decay of calcium atoms (the Clauser test), photon polarizations are the same for L and R: $\Phi^\pm = |11\rangle \pm |00\rangle$.

The Venn diagram overlaps still represent ABC as say a = 1 or $\bar{a}$ = 0. To reduce triplets to just pairs, use $ab = abc + ab\bar{c}$ where c + not c = $c + \bar{c}$ is "all of C".

The simple case shown in Wikipedia has A = Alice and B = Bob and their results together. Let X= $\bar{a}\bar{b}$+ $\bar{a}$b + a$\bar{b}$ -ab = ($\bar{a}$ +a)$\bar{b}$ + ($\bar{a}$ -a)b. Now both a and $\bar{a}$ have values 0 or 1 so either a = $\bar{a}$ or a = -$\bar{a}$ results in ± 2$\bar{b}$ or ± 2b. Hence, $|\langle X \rangle| \leq 2$ called the CSCH inequality. SINGLET examples supposes anti-correlation ↑ +↓ = 0; but that is not the Clauser Bell State in which two photon polarizations are parallel. Bell-type theorems do not refer to any particular theory of local hidden variables, but instead show that quantum physics violates general assumptions behind classical pictures of nature.

Solutions to Bell: **"Render nonlocality compatible with relativity, by making it an indirect, partially retrocausal process, acting via the past light cones of the two observers.** This requires that we abandon an assumption of Bell's argument called Statistical Independence (SI), to allow measurement choices to influence hidden variables (HVs) in their past."

The transactional interpretation (TI) [Cramer] supposes sub-space amplitude level information being passed forwards and backwards in time until conservation laws are satisfied.

Comment by [Mead] "the TI's assertion that the offer wave ↗ "stimulates the generation of the confirmation wave" ↙ must be modified. Rather, advanced and retarded potentials, boundary conditions at **both ends, and a fortuitous matching of phase trigger the nonlinear avalanche in both atoms** and brings about the transaction. … , leading dynamically to an initially exponential rise in coupling, a focusing of alternative paths, the formation of a transaction, a transfer of energy, **and the enforcement of conservation laws.** {And also see [Healey]}.

Superconductivity: The BCS state describing a conventional superconductor is indeed **an entangled state**, involving a superposition of different numbers of Cooper pairs, each of which involves a superposition of different combinations of paired momenta. An important thing about the BCS state is the specific way in which the electrons are entangled with each other. BCS superconductivity relies on the fact that many Cooper pairs can occupy the same "state, https://physics.stackexchange.com/questions/492986/are-cooper-pairs-of-electrons-entangled

It turns out that Schrieffer's ansatz for the BCS ground state WF is a **Coherent State** of Cooper pairs, although the explicit concept of such a state did not yet exist (until 1963).

Bohr's statement that observers see particles implies that interactions involving waves evoke particle-like behavior. Wave amplitudes obey unitarity but not necessarily conservation laws. "Collapsed waves" obey conservation laws. The enforcement of those laws suggests handshaking agreements between sources and detections. Squaring amplitudes follows naturally from the "handshake" of waves going both forwards and backwards in time. And probability might result from a need for phase agreements between source and receiver (as demonstrated for photons by Mead).

{Email to Mike Jones, 7/1/24}"

I think the Aharonov-Bohm location phase shifting is still a special conceptual problem. We have a rotary $\vec{A}$ field just after the slits and say the upper (beam of single) electron wave ray has e$\vec{A}$ adding to its m$\vec{V}$ momentum and the lower electron wave ray has e$\vec{A}$ subtracting from it. The phase shift depends on full charge **e** being present above and below the tiny solenoid -- two places at once. The Schrodinger-Pauli equation just provides a summary-ψ of phase effects from potentials but avoids the how's ("reality" is badly underdetermined). At least in "amplitude space" {note that I'm trying not to say "square-root-of-reality space"} the electron charge presence has to be felt in both spatial locations. Bohm tries to say the charge went through one slit, but he uses the summary psi function which already accounted for charge being present in rays from both slits. For the case of single neutrons, we have spin and magnetic moment having to have a felt presence in both paths (and Zeilinger added gravity altitude effects too). And experiments can add two separate Helmholz coils to two paths for $\vec{B}$-precessions. I see this issue as a key one *for driving people crazy trying to understand the impossible*. None of the present interpretations work perfectly -- some new (perhaps weird) thinking seems to be needed. QFT doesn't seem to be tangible enough to help explain all of QM. The quantum rules say an electron can be in two places at once, and almost every physicist will simply quote those rules. But, I'm asking "what are the mechanisms explaining the rules – such a question was not previously encouraged.

In QFT, the concept of position is considered a label rather than a dynamical variable. Fundamental particles "are described as excitations of quantum fields, which are defined throughout space and time. The position of a particle is not a fixed or well-defined quantity, but rather a probabilistic distribution represented by the wave function." We might say that the position of electron charge is "fuzzy," but it has a peculiar kind of tapering off with distance. The presence may become weaker, but the particle properties are not {full electron charge, magnetic moment, spin and mass at each location of influence}.

New Summary Perspectives:

Rather than being the primary reality, a wavefunction ψ(x,t) is a summary representation for knowledge of possible system outputs from an experiment. We do accept "waves" in general as an aspect of reality in the "amplitude space" of quantum mechanics. But if ψ represents a statistical ensemble of similarly prepared objects, then it might be more mathematical than physical. By the dominant convention, psi is called a wave of probability amplitude. But, it could be that it is really energy amplitude with an {apparently random} event selection mechanism proportional to energy density of the a final wave prior to measurement. Energy is coded as the density of waves in time, and momentum is coded as density of waves in space. ψ only represents contributions of these composite energy/momenta in waves and does not itself contain particle properties. A fault of traditional QM is that it totally ignores possible underlying mechanisms (they are not allowed to exist).

The deeper underlying QM physics leading to psi must somehow include full-value particle properties traveling with propagating waves (a vague term is "wavicles"). Presently, particle properties such as charge are only present in the Hamiltonian operating on ψ – and, underlying quantum mechanisms are hidden beneath the operator formalism. As an example, the presence of a full electron charge, e, in multiple spatial locations is already "assumed" to go along with a wave for cases such as the Aharonov-Bohm-effect (using $e\vec{A}$ in both slit rays) and electron biprism splittings (using eϕ on opposite sides of a charged thin wire). Another example is the presence of spin and magnetic moment in both paths of a neutron crystal interferometer.

"An electron is a highly-unified spatially-extended bundle of quantized field energy" {Art Hobson, QFT}. So, perhaps a more appropriate primitive reality is fuzzy wavicle where both the wave-tone span and the particle properties spatial range of fuzziness are overlapping to the same extent and travel together {a "particle" is not a point until it has a major interaction}. These still have the QM properties such as amplitude superpositions and entanglements. The single particle wavicle is somewhat ameboid in its ability to branch off portions of itself after a stimulus. In its own frame of reference (or center of presence), a charged wire (biprism) forces a split in half; and, the two spatially separating halves are "holistic" as magically still one unity (the term "entangled" generally refers to multiple particles). One view towards understanding this is back-and-forth-in-time connectivity between all parts even within a single "quanta." So we now mean "holistic" over both space and time together {although some would call this "beyond space-time" because it doesn't yet honor the "arrow of time"}. Such a space-time holism also helps understanding of multiple particle entanglements. And it can also assist in understand a dovetailing of mechanisms that enable enforcement of conservation laws in multi-particle scatterings.

Other Assorted Views:

Aharonov: "we contend that the wave function is appropriate as an ontology for an ensemble rather than an ontology for an individual system. Our principle justification for this is because the wave function can only be directly verified at the ensemble level."

"Wave-particle duality indicates that wave property and particle property **could coexist"** {at least for photons where particle number need not be conserved}.
https://iopscience.iop.org/article/10.1088/2399-6528/abfd15/pdf **"Single-photon entanglement** is a type of entanglement that occurs between a single photon and two spatial modes, or between a vacuum state and a single-photon state. It's a fundamental aspect of quantum mechanics and is essentially the entanglement of particle characteristics.

https://iopscience.iop.org/article/10.1088/1367-2630/18/4/043036 **"Single-electron entanglement and nonlocality** "The field of electron quantum optics has witnessed strong experimental advances over a short period of time [1]. Electronic analogues of the Mach−Zehnder [2], Hanbury Brown−Twiss [3] and Hong-Ou-Mandel interferometers [4] can now be implemented with edge channels of the integer quantum hall effect functioning as wave guides for electrons. At the same time, the recent realization of coherent single-electron emitters is opening up avenues for the controlled manipulation of few-particle electronic states

"an electron is a highly-unified spatially-extended bundle of quantized field energy} {Art Hobson}. Electron charge as a single entity is a classical construct. Until it is "measured," it is a propagating electron field disturbance with presence in many superimposed locations. (charge-ness and electron-ness as "forms" of the universal Vacuum – and Nature is made of Fields). Wavefunctions and Tones "have a strongly non-local character" as holistic entities [Penrose]. Particles exist in all possible realities at once until they are measured. Despite a widespread presence, a final single-only event emerges in accord with conservation laws (as there is only one charge present, and it is absolutely conserved).