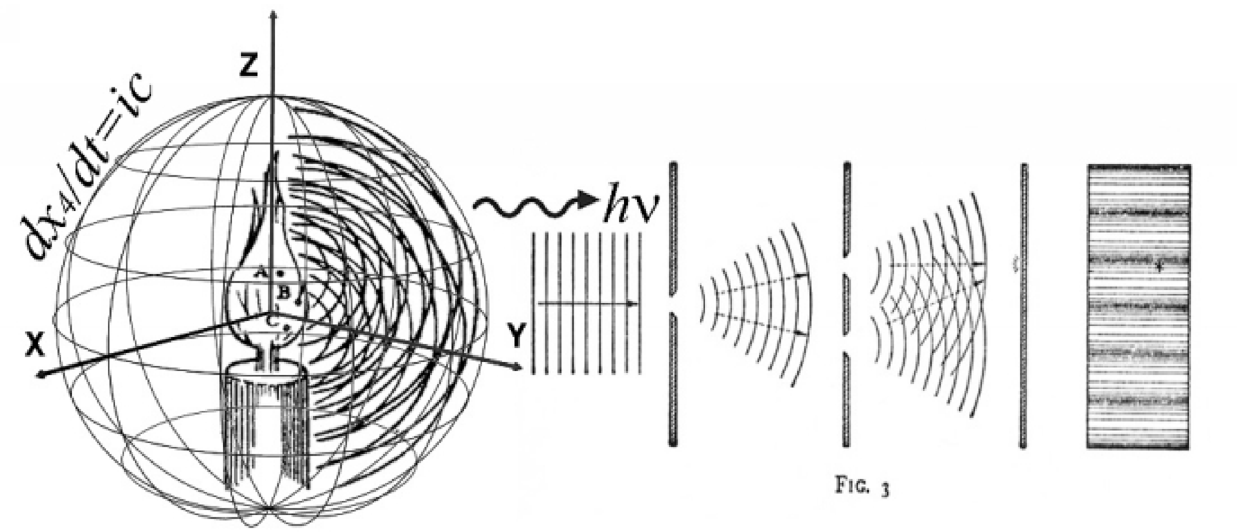
Princeton Afternoons with Noble and Nobel Physicists (the Birth of $dx_4/dt=ic$) & A Paper on Quantum Entanglement with John Archibald Wheeler and Joseph Taylor at Princeton University -- *Within a Context: A Discussion of Paradoxes in Quantum Theory between Curiosity and Perseverance*

by Dr. Elliot McGucken



1. Princeton Afternoons with Noble and Nobel Physicists (the Birth of $dx_4/dt=ic$)

> Albert Einstein: The supreme task of the physicist is to arrive at those universal elementary laws ($dx_4/dt=ic$) from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them. From "Motives for Research," a speech delivered at Max Planck's sixtieth birthday celebration, April 1918. Reprinted in Ideas and Opinions, 226, as "Principles of Research." See CPAE, Vol. 7, Doc. 7

Back when the string theory juggernaut of institutionalized failure was preparing to conquer the world and vanquish physics, I found myself running by Ed Witten's office every day. It was my junior year at Princeton and the outlandish hype proclaiming Witten to be the next Einstein had recently been published in the *NYT*. Back then, string theory had no physical postulates, principles, nor equations. Today, despite stealing yet one more generation's livelihood via hype, lies, and deceit, while further entrenching thousands of failed, snarky elite group-thinkers in the ivory towers, string theory *still* has no physical postulates, principles, nor equations. And it has metastasized and influenced numerous other failed research programs including M-Theory, multiverse mania, inflation, and others. Once it was recognized that all the money was in regions that could never be measured nor visited married to murky, meaningless math, the natural group-thinkers and haters of Western Civilization banded together to build a temple worshipping the very antithesis of science and philosophy—the very opposite of truth, beauty, and poetry. The failure of string theory was so fantastically epic that it not only provided jobs, titles, benefits, and lavish conferences in luxurious locales for tens of thousands of group-thinkers and pyramid-scheme con-artists, but it also provided full-time jobs to detractors of string theory and controlled opposition, who sometimes pretended to criticize it for clickbait links to their physics-free blogs.

Back in my Princeton days, Wheeler, Peebles, Taylor *et al.* were not buying string theory. As Men of Honor, they shared R.P. Feynman's view on the pseudoscience of string theory: "I do feel strongly that this is nonsense!"

Witten's office at the Princeton Institute for Advanced Study (IAS), situated in-between pastoral fields and a deep forest, was just down the road from where I resided. As I loved the outdoors, the IAS's woods became my oasis of peace and quiet in New Jersey. I loved nature as she was not affected by the vicious postmodern physicists and poets who were violently deconstructing physics and literature upon the Princeton campus. And as the Great Books and Physics only succeeded to the degree that they exalted Natural Truth and Beauty, I knew that at the end of the day, the violent false suitors would only succeed in deconstructing their own spirits and soul—they would only succeed in their own dishonorable, fiat failure.

One fine afternoon, just before I went running, I decided to visit my advisor John Archibald Wheeler (Princeton's Joseph Henry Professor of Physics) in his third-floor Jadwin Hall office, as I had a question that had been bothering me. It was the fall of my junior year at Princeton, whence we were called upon to initiate the creative research (that would ultimately determine whether or not we were true, heroic physicists!) by working on an independent project. While I could never pay attention in class, and while I never took a single note during my entire Princeton career, I received straight A's on all my independent research, conducted with the likes of J.A. Wheeler and Nobel Laureate Joseph Taylor.

As I walked through Wheeler's always-open door, I found him looking out the window at the brilliant autumn foliage. His book-filled, paper-strewn office harkened of the swirling, falling leaves outside, as if the same wind arranged both systems. The distinguished Wheeler slowly turned, dressed in his classic suit and tie, his hand gently clenched in a fist holding a piece of chalk:

“Today’s physics lacks the *Noble*,” he stated in his quiet, raspy voice, his blue eyes smiling, “And it’s your generation’s duty to bring it back.”

I nodded and paused a bit. But I couldn’t wait to ask my question: “So a photon doesn’t move in the fourth dimension?” I inquired, continuing our conversation from a week earlier. “All of its motion is directed through the three spatial dimensions?”

“Correct.” Wheeler said.

“So a photon remains stationary in the fourth dimension?”

“Yes.”

Later that afternoon, I found myself in P.J.E Peebles’ (the Albert Einstein Professor Emeritus of Science) office, as he was my professor for quantum mechanics. Many argued that Peebles should have been awarded the Nobel in physics for predicting the microwave background radiation shortly before it was accidently discovered by Arno Penzias and Robert Woodrow Wilson as they experimented with the Holmdel Horn Antenna. In Peebles’ class we were using the galleys for his upcoming textbook *Quantum Mechanics* (now in print—buy one—it’s an epic treatise!) for his two-semester course.

“So in the simplest case,” I began my question to Professor Peebles, “When a photon is emitted from a source, it has an equal chance of being found anywhere upon a spherically-symmetric wavefront expanding at the rate of *c*?”

“Yes.” PJE Peebles stated.

It wasn’t until years later when I was working on my NSF-funded, award-winning artificial retina Ph.D. dissertation (which is now helping the blind see!), that I realized that as the photon remains stationary in the fourth dimension, it provides the ideal tracer for the motion of the fourth dimension. In the same way that a small GPS tracer tagged to an eagle remains stationary relative to the eagle as it soars through the air, thusly tracking the eagle’s motion in flight, a photon, which remains stationary relative to the fourth dimension, must track its motion. Thus, because a photon is described by a spherically-symmetrically wavefront expanding at the rate of *c* while remaining stationary in the fourth dimension, the fourth dimension must be expanding at the rate of *c*, manifesting a spherically-symmetric wavefront of nonlocality expanding through the three spatial dimensions at the rate of *c*.

I would often take a break from my dissertation research by reading the foundational papers of physics penned by the likes of Einstein, Bohr, Planck, Heisenberg, Wheeler, Bell, Maxwell, Newton, Huygens, Galileo, Copernicus, *et al*. While I could have pursued string theory or inflation theory, as soon as I found out that they didn’t really have any real equations nor made any actual predictions, I elected not to participate nor promulgate the purely political hoaxes. Wheeler also agreed with his great graduate student—the Nobel Laureate R.P. Feynman:

> I do feel strongly that (String Theory) is nonsense! … I think all this superstring stuff is crazy and is in the wrong direction. … I don't like it that they're not calculating anything. … Why are the masses of the various particles such as quarks what they are? All these numbers … have no explanations in these string theories – absolutely none! … I don't like that they don't check their ideas. I don't like that for anything that disagrees with an experiment, they cook up an explanation—a fix-up to say, "Well, it might be true." For example, the theory requires ten dimensions. . . When they write their equation, the equation should decide how many of these things get wrapped up, not the desire to agree with experiment. . . . it doesn't produce anything. –R.P. Feynman Interview published in Superstrings: A Theory of Everything? (1988) edited by Paul C. W. Davies and Julian R. Brown, p. 193-194 ISBN 0521354625

Unlike the superficial, snark-filled blogs and millions of meaningless arxiv.org papers that were intentionally mired in indecipherable, fallacious maths and deviously faulty reasoning, the primary element of the foundational papers of physics were *words of honor and nobility*. The beautiful grandeur and nobler soul of physics is completely absent from the failed string theorist's/YouTube diva's self-indulgent, hand-wavy, snark-filled videos created not to exalt and illuminate with Truth, but to degrade and debauch—to transform all of physics into their own petty, fallen likeness.

One fine afternoon on a windsurfing trip, while taking a break for a late lunch, I found myself leafing through Einstein's *1912 Manuscript on Relativity*—a masterpiece of simple physics married to profound, meaningful mathematics. Suddenly, like a bolt from the blue—it hit me. The Minkowski-inspired equation $x_4=ict$ had a *physical* meaning! It told of the expansion of the fourth dimension relative to the three spatial dimensions, thusly providing not only the foundations for relativity, but for quantum entanglement, time's radiative arrow, and the second law of thermodynamics! Have you ever wondered why x_4 is the only coordinate related to t in the spacetime metric? It is because the fourth dimension is expanding relative to the three spatial dimensions, or $dx_4/dt=ic$!

Suddenly I saw, clear as day, the *physical* mechanism of time and all its arrows and asymmetries. I saw the foundational source of relativity, quantum nonlocality and entanglement, entropy's one way-arrow, the second law of thermodynamics, dark energy, dark matter, and the vacuum energy! With a single, bold *physical* thought I had liberated us from the block universe and exalted free will. The very nonlocality and probability in quantum mechanics came from the nonlocal expansion of the fourth dimension relative to the three spatial dimensions! Because the expansion of x_4 was symmetrical, every point on the expanding 3D sphere it manifested was equivalent! The fourth dimension itself exhibited nonlocal properties as it expanded, and as all points on its spherically-symmetrically expanding surface were equivalent, the particulate momenergy of the photon had an equal chance of being found anywhere upon the surface. The fourth dimension itself was nonlocal via its expansion! Are not nonlocality and entanglement empirical elements of our reality? Must they not have some physical foundation and cause, and should not relativity and time and all its arrows also rest upon this common *physical* foundation and cause? For nonlocality, time and all its arrows, relativity, and entanglement are all empirical properties of our *physical* reality! The expansion of the fourth dimension exalted wave-particle duality, space-time duality, E-B duality, and mass-energy duality!

Because the fourth dimension is moving at c relative to the three spatial dimensions, a mass in our lab is thusly moving at c relative to the fourth dimension, thereby endowing it with a vast energy given by $E=mc^2$, which is directly derived from $dx_4/dt=ic$ in this book. $dx_4/dt=ic$ exalts a more concise way of encapsulating Einstein's two postulates of relativity while also providing the foundational physical reality underlying relativity which Einstein yet sought, as well as providing a *physical* model and mechanism for quantum nonlocality and entanglement, which Schrodinger deemed the "characteristic trait of quantum mechanics."

It had been the spring of my junior year at Princeton University when I had first encountered Schrodinger's epic statement on quantum entanglement:

> When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that one but rather the characteristic trait of quantum mechanics," the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled. To disentangle them we must gather further information by experiment, although we knew as much as anybody could possibly know about all that happened. Of either system, taken separately, all previous knowledge may be entirely lost, leaving us but one privilege: to restrict the experiments to one only of the two systems. After reestablishing one representative by observation, the other one can be inferred simultaneously. In what follows the whole of this procedure will be called the disentanglement... ("*Discussion of Probability between Separated Systems*", Proceedings of the Cambridge Physical Society 1935, 31, issue 4, p.555)

I remember hanging out in soon-to-be Nobel Laureate Joseph. Taylor's office who was both my professor for experimental physics as well as my advisor for my junior paper on quantum nonlocality, entanglement, the EPR Paradox, and delayed-choice experiments. Taylor stated, "Schrodinger said that entanglement is the characteristic trait of quantum mechanics. Figure out the source of entanglement, and you'll figure out the source of the quantum, as nobody really knows what, nor why, nor how *ħ* is." The remarkable thing that I now realize is how the Greats pondered the Great Questions. One can search through ten years of a pop-science blogger's ramblings and never once come across the sentiment that physics is about finding the deeper causes of observed phenomena such as entanglement, the second law of thermodynamics, and time dilation. While LTD Theory provides a *physical* mechanism for quantum entanglement, nonlocality, and its probabilistic nature (and so much more!), the failed groupthink projects of string theory, multiverse mania, inflation, and LQG completely ignore such foundational questions, choosing never-ending snark, lies, and hype over physics.

J.A. Wheeler kindly wrote:

> "I gave (Dr. E) the proofs of my… *A Journey into Gravity and Space Time*… the space part of the Schwarzchild geometric is worked out by purely geometric methods. "Can you, by poor-man's reasoning, derive what I never have, the time part?" He could and did, and wrote it up in a beautifully clear account. . . .his second junior paper . . . was done with another advisor (J. Taylor), and dealt with … the Einstein-Rosen-Podolsky experiment and delayed choice experiments... this paper was so outstanding…" And so Dynamic Dimensions Theory (MDT) would be born as a unifying, foundational physical model for both the "elementary foundations" of relativity that Einstein yet sought and Schrodinger's "characteristic trait" of QM—entanglement, showing that both relativity and the discrete, digital nature of energy and measurement arose from the discrete geometry carved into space-time by x4's expansion, which parcels mass and energy in discrete units proportional to ħ as it propagates at c.

Because a photon exists in a state of pure motion, surfing the expanding fourth dimension, it has zero rest mass, meaning none of it is at rest in the three spatial dimensions as it travels. I realized that there was a frame of absolute rest—the three spatial dimensions—and a frame of absolute motion—the fourth expanding dimension. But due to the tautological relationship between time, measurement, light, and length inherent in the spacetime metric, it is difficult to observe differences in inertial frames. However, as we can measure our motion relative to the CMB, it does appear that there is a frame of absolute rest (the three spatial dimensions), and thus a frame of absolute motion (the fourth expanding dimension). All of this is apparent in the standard spacetime metric, where, for some reason, now at long last given by LTD Theory, only the fourth coordinate is time-dependent.

Wheeler oft referred to the direction of particle physics as "ino-itus" whence more and more funding was spent pursuing smaller and smaller particles and details, void of novel grand ideas or new foundational, *physical* insights. The LHC is perhaps a noble accomplishment overshadowing string theory's fantastical farce, but when history is written, we can be sure that a lone patent clerk named Einstein will have made a greater contribution to physics in 1905 with naught but a pencil, a piece of paper, a courageous and free imagination, and an unyielding loyalty to *physical* Truth exalted by a *physical* interpretation of the mathematics. Wheeler, like the heroic physicists of yore, was in physics for the big *physical* ideas, much like Einstein who wrote, "I want to know God's thoughts; the rest are details."

When Wheeler sadly passed away a few years back, Colby Cosh saluted the giant with:

> "At 96, he had been the last notable figure from the heroic age of physics lingering among us. . . the student of Bohr, teacher of Feynman, and close colleague of Einstein. . . Wheeler was as much philosopher-poet as scientist, seizing on Einsteinian relativity early . . . He was ready to believe in the new world before most physicists. . ."

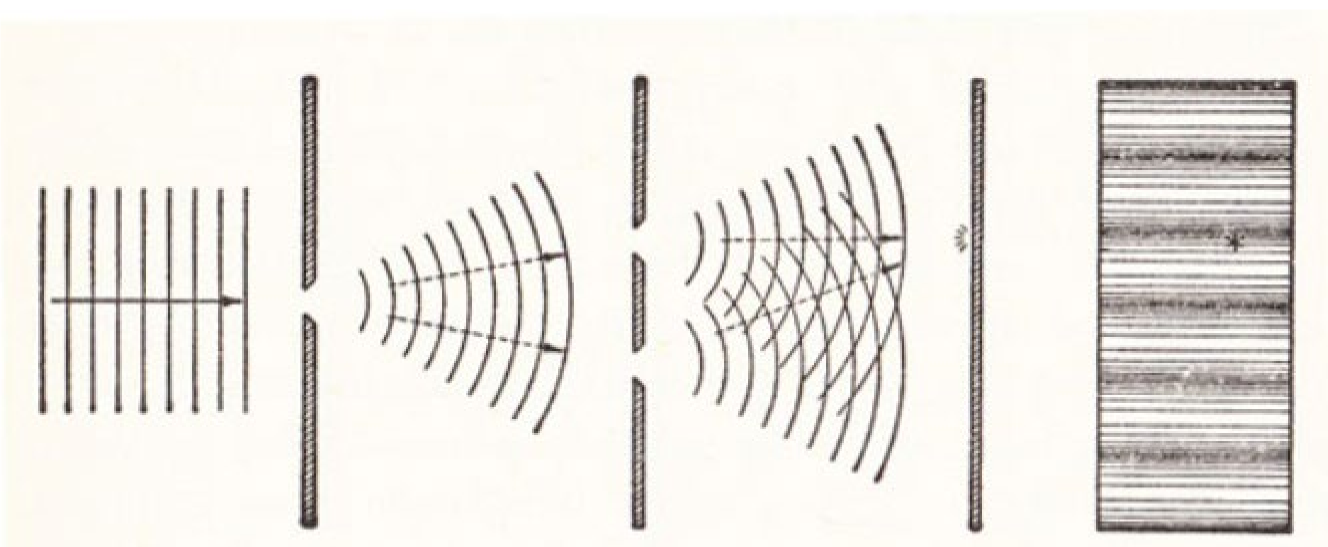


FIG. 3

The above figure presents an illustration from a paper authored by Wheeler's teacher Bohr which I first saw in Wheeler's compilation *Quantum Theory and Measurement*, which I happened upon in my freshman dorm. The illustration pertains to the classic double-slit experiment, of which Wheeler's student Feynman was fond of stating, "The whole of quantum mechanics can be gleaned from pondering the implications of the double-slit experiment. . . it is a phenomenon which is impossible […] to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery [of quantum mechanics]." And thus one can see why the string theorist and professional "physics" blogger ignore the Truth of the simple, foundational experiment, instead waving their hands and using it as "proof" of their many-worlds and multiverse regimes, as the millions of fiat dollars flow into their burgeoning bank accounts inflated via misinformation, hype, and lies—via cultural and monetary debasement.

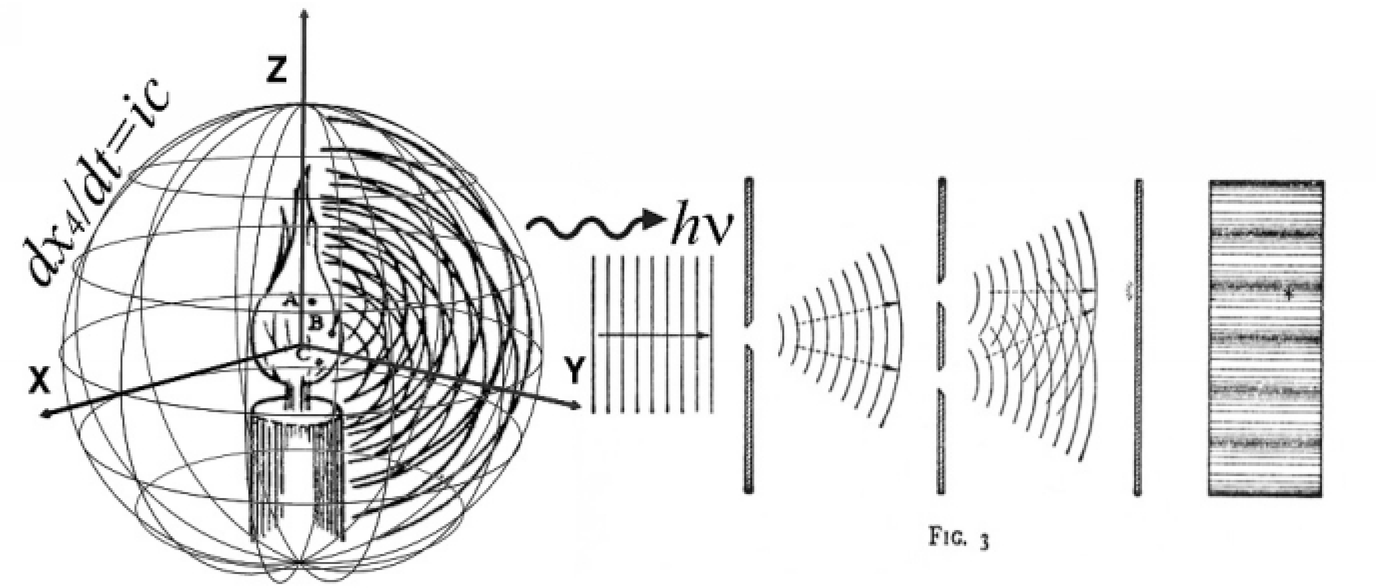


FIG. 3

The above double-slit diagram illustrates the wavelike nature of all particles, including the photon. But what Bohr, Einstein, Feynman, *et al*. seemed to have missed was that they were looking not only at the motion and character of the photon, but they were looking at the motion and character of x_4, as relativity dictates that the ageless photon remains stationary in the fourth dimension, meaning that the photon provides an ideal tracer following the movement of x_4. Thus we can conclude that not only is x_4 a spherically-symmetric wavefront expanding at *c*, distributing locality into nonlocality and giving rise to entanglement and entropy as well as time and all its arrows and asymmetries, but it is also oscillating in a quantized manner, thusly quantizing all energy it carries in discrete packets, which in turn quantizes all measurement, as measurement hinges upon the propagation of energy—photons.

And too, LTD Theory presents a *physical* model and explanation of Huygens' Principle which stipulates that every point on a spherically-expanding wavefront defined by the photon is itself the source of a spherically-expanding wavefront. As Huygens' wrote in his 1678 manuscript *Treatise on Light*:

> In which are explained The causes of that which occurs
> In REFLEXION, & in REFRACTION And particularly

> In the strange REFRACTION OF ICELAND CRYSTAL, "So it arises that around each particle there is made a wave of which that particle is the center.

If one wishes to see an authentic, noble piece of science writing which shall far outlast all the Stringy hype that *Scientific American* uses to sell misleading, science-bastardizing magazines, read the beautiful words of Huygens' masterwork here: http:/www.gutenberg.org/files/14725/14725-h/14725-h.htm

Finally, for the first time in all of history, an actual mechanism was given for the Huygens'-Fresnel principle. The fourth dimension itself is expanding as a spherically-symmetric wavefront at the rate of *c*, and thus every point is continually becoming a spherically-expanding wavefront in its own right, distributing locality and fathering probability, as a photon caught in the expanding fourth dimension has an equal probability of being found anywhere upon the surface of the sphere defined by its expansion.

MathPages reports on a foundational question regarding Huygens' Principle that LTD THEORY answers for the first time in all of history, writing:

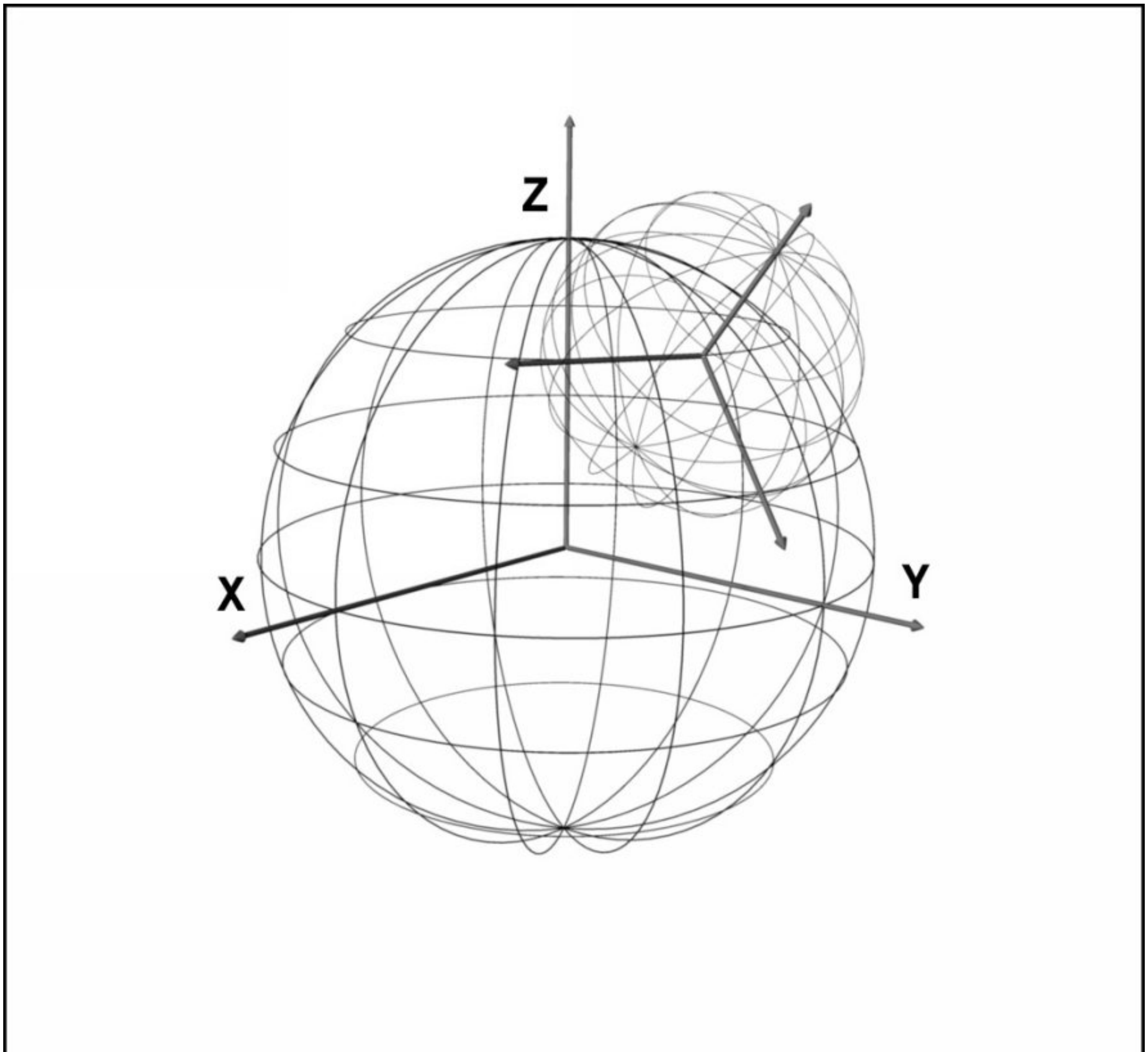
> "From this simple principle Huygens was able to derive the laws of reflection and refraction, but the principle is deficient in that it fails to account for the directionality of the wave propagation in time, i.e., it doesn't explain why the wave front at time t + Dt in the above figure is the upper rather than the lower envelope of the secondary wavelets. Why does an expanding spherical wave continue to expand outward from its source, rather than re-converging inward back toward the source?"
> http://www.mathpages.com/home/kmath242/kmath242.htm

For the first time in the history of physics, LTD THEORY accounts for this foundational asymmetry. An expanding spherical wave continues to expand outward from its source because that is the foundational motion of the fourth expanding dimension and thus the foundational motion of the universe. I had resolved the paradox that had puzzled my advisor Wheeler and his graduate student Feynman back in the day. Wikipedia reports on the Wheeler-Feynman absorber theory:

> The Wheeler–Feynman absorber theory (also called the Wheeler–Feynman time-symmetric theory) is an interpretation of electrodynamics derived from the assumption that the solutions of the electromagnetic field equations must be invariant under time-reversal symmetry, as are the field equations themselves. Indeed, there is no apparent reason for the time-reversal symmetry breaking which singles out a

preferential time direction and thus makes a distinction between past and future. -- http://en.wikipedia.org/wiki/Wheeler%E2%80%93Feynman_absorber_theory

The expansion of the fourth dimension, described by $dx_4/dt=ic$ and illustrated in the figures exalting McGucken's Sphere throughout this book is the reason for the symmetry breaking.



McGucken's Sphere

The fourth dimension is expanding, not contracting, and thus time and all its arrows and asymmetries, Huygens' Principle, entropy and the second law of thermodynamics, quantum nonlocality and entanglement, relativity's time dilation, the constant velocity of light *c*, and equivalence of mass and energy, E and B, space and time, as well as wave-particle duality. Wikipedia goes on to defend the theorized Wheeler-Feynman time symmetry with, "A time-reversal invariant theory is more logical and elegant." But it's not. A sock-puppeting string theorist must have written this, as if a theory fails to match up to physical reality, they conclude that it is naturally "more logical and elegant." This reminds me of the legend of the "Bed of Procrustes." Procrustes was a most generous host who would offer all his guests a nice bed during their stay. If the bed was too big or too small, he would kindly make adjustments. The only problem was, he would make adjustments in the guest instead of the bed, chopping their feet off or stretching their body out to make them fit. He would call this "more logical and elegant," and had he been alive today, he would likely be a YouTube "science" star alongside the pretty string theory divas filming themselves slicing four dimensional loaves of bread.

Huygens' Principle is a far-reaching beautifully *asymmetrical* phenomenon, representing the nature's foundational asymmetry—the one-way expansion of the fourth dimension, which is the causal mechanism of time's arrows and asymmetries. Each point on an expanding wavefront is in turn an expanding wavefront. And not only does this reality manifest itself in light and wave pools in freshman physics labs, but it is also foundational to Feynman *et al.*'s Quantum Electrodynamics (QED). This makes perfect sense, as the expansion of the fourth dimension relative to the three spatial dimensions is the very foundation of all motion, as well as of time and all its arrows and asymmetries, including entropy and the second law of thermodynamics.

Numerous sources, including Wikipedia, report on the well-known link between Huygens' Principle and Quantum Electrodynamics (QED). Wikipedia reports:

> Huygens' Principle can be seen as a consequence of the isotropy of space—all directions in space are equal. Any disturbance created in a sufficiently small region of isotropic space (or in an isotropic medium) propagates from that region in all radial directions. The waves created by this disturbance, in turn, create disturbances in other regions, and so on. The superposition of all the waves results in the observed pattern of wave propagation.
>
> Isotropy of space is fundamental to quantum electrodynamics (QED) where the wave function of any object propagates along all available unobstructed paths. When integrated along all possible paths, with a phase factor proportional to the path length, the interference of the wave-functions correctly predicts observable phenomena. Every point on the wave front acts as the source of secondary wavelets that spread out in the forward direction with the same speed as the wave. The new wave front is found by constructing the surface tangent to the secondary wavelets. --
> From: http://en.wikipedia.org/wiki/Huygens%E2%80%

93Fresnel_principle#Huygens.27_principle_and_quantum_electrodynamics

And so it is that LTD's simple principle underlies not only Huygens' Principle, but QED. This alone would be a great distinction, but LTD Theory's simple principle of a fourth expanding dimensions also allows us to derive all of relativity, which we will do throughout the rest of this book.

2. A Paper on Quantum Entanglement with J.A. Wheeler and Joseph Taylor at Princeton University -- *Within a Context: A Discussion of Paradoxes in Quantum Theory between Curiosity and Perseverance*

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Within a Context:
A Discussion of Paradoxes in Quantum Theory between Curiosity and Perseverance

by Elliot McGucken
Advisors: Joseph Taylor
John A. Wheeler

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We have always had a great deal of difficulty,
understanding the world view,
that quantum mechanics represents.

At least I do,
because I'm an old enough man,
that I haven't got to the point,
that this stuff is obvious to me.

Okay, I still get nervous with it. . .

You know how it always is,
every new idea,
takes a generation or two,
until it becomes obvious that there is no real problem.

I cannot define the real problem,
therefore I suspect there is no real problem,
but I'm not sure,
that there's no real problem.

-- R. P. Feynman's comments on the Einstein Rosen Podolsky paradox, quoted in *Physics Today*, Vol. 38, No. 4, p. 47.

WITHIN A CONTEXT

I. The EPR Paradox

Perseverance: So, my friend, what brings you here?

Curiosity: Lately I have been wondering about many things. . . I have been wondering what exactly it is that makes me a conscious observer. Why are we here, and what does it mean to exist?

Perseverance: I am glad to hear of your curiosity, for curiosity is a beautiful sign of existence, but I am afraid that you may be disappointed -- I am not sure what it is that makes us conscious observers. As far as understanding existence itself, I know very little, if anything at all.

Curiosity: But people have told me you are very wise. . .

Perseverance: That may be so, in the context of certain games, but upon closer examination, I find that all I know becomes intangible when I attempt to reach out and grasp it firmly. When we communicate, there is an implicit context in which all of our words reside, and it is in this context that our words take on meaning and form our pictures of reality. As we grew up and developed, our minds received and stored information in an ordered manner. Connections were established in our brains, and it are these connections which form the implicit context in which we think. All new information is interpreted by the existing connections and it is perhaps a certain number of these connections which gives rise to consciousness. When two people have parallel implicit contexts, they can exchange information in an ordered way, and we call this communication.

Curiosity: Wait! First you tell me you know nothing, and then you tell me all this!

Perseverance: As far as the fundamental essence of existence is concerned, I know nothing. But I do know how to play games within defined contexts. Whether we play the game of art, music, science, or language, we are merely offering a description of the reality we perceive and the truths we feel, all which arise from connections within our minds. However, outside the realms of these games, I know *nothing*. I am unable to reach beyond the boundary of these games, into some undefined context, but I expect that someday our curiosity might lead us there.

Curiosity: You say it is all just a game, but I have to disagree! Literature is more than a game, for there is much to be learned from it! It tells us about mankind and human nature! And philosophy, the love of knowledge, surely it is more than a game!!

Perseverance: We interpret combinations of words according to the implicit context in which we think. However, this context is arbitrary and can be shifted to one side or another, as Plato demonstrated with his dialogues in the Protagoras. Bohr[1] said, "we are suspended in language in such a way that we cannot say what is up and what is down." We quickly find that the reality one observes is a relative experience, depending upon the context in which one thinks, and the direction in which one happens to be looking. As Wheeler[1] demonstrated in his game of twenty questions, the illusion one perceives depends upon what questions one decides to ask.

Curiosity: You seem to be making it much too complicated, much too abstract. . . I like what Leibniz[2] said, "Although the whole of this life were said to be nothing but a dream and the physical world nothing but a phantasm, I should call this phantasm real enough if, using reason well, we were never deceived by it." And it is John Bell's feeling[3] that, "one wants to be able to take a realistic view of the world, to talk about the world as if it is really there, even when it is not being observed." I must say that I, like Samuel Johnson, only have to kick a stone to find it real enough[1].

Perseverance: When we speak of reality, we can only offer our personal interpretation. As evolutionary animals, the ability to define and function within a reality is essential to our survival. And so we adopt an interpretation of reality, and play the game to which we are best suited.

Curiosity: There must be something more to it all than just games! There must be a plan!

Bohr?

Perseverance: Throughout his life, Bohr held fast to the idea of "Complementarity;" one can know either the position or the momentum of a particle at an instant in time, but one cannot know both. Bohr's comment[6] on the proposed EPR paradox was,

> "From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by EPR contains an ambiguity as regards the meaning of the expression, 'without in any way disturbing a system.' Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical state of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system.* Since these conditions constitute an inherent element of the description of any phenomenon to which the term 'physical reality' can be attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete."

Curiosity: So Bohr refers to some type of an "influence" which must result from an action at a speed greater than that of light. Suppose we adhere to Einstein's locality postulate, based on relativity, which asserts that there can be no influence that is propagated faster than light. Is there some type of resolution to this apparent paradox?

Perseverance: Yes, there is a resolution in which we introduce the concept of the hidden variable. The motivation for the introduction of this concept was the belief that the motion of individual systems is strictly deterministic at a more profound level[4,13]. With the presence of hidden variables, one can think of quantum theory as being analogous to statistical mechanics which yields only average values of measured quantities.

Curiosity: But wait, along those lines of reasoning, one could then suppose that there are laws governing these hidden variables, and then maybe these laws, in turn, are merely average values of measured quantities. . . And could we not continue to extend this argument ad infinitum, to suit all of our needs? Do you really believe that the universe may be founded upon an infinite array of turtles[2] stacked upon each-others backs? Do you believe hidden variables *really* exist?

Something which exists independent of us!

Perseverance: Oh, I fully agree that there must be something more, but as to what the particular nature of this "something more" is, we have only the views offered us by our personal philosophies, which are subjective. We must remember how easy it is to lose ourselves in dreams of language.

Curiosity: Then how about Physics? Surely it offers insight into the nature of reality.

Perseverance: Perhaps, but we must be careful. In physics too, we encounter many different opinions as to what the fundamental plan of it all is. Einstein[1] said that, "Physics is an attempt to grasp reality as it is thought independently of its being observed." However, Bohr believed that one can't separate the act of observation from the concept of reality. His reply to Einstein was,

> "These conditions (of measurement) constitute an inherent element of any phenomenon to which the term 'physical' reality can be attached. This requires a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality."

Heisenberg[4,13] shared this view with Bohr, and he expressed the Copehenhagen interpretation which states that quantum theory is just a set of mathematical rules to predict future observations;

> "There exists a body of exact mathematical laws, but these cannot be interpreted as expressing simple relationships between objects existing in space and time." According to this view, no attempt is made to describe the "reality" of the quantum system between measurements.

Curiosity: There has to be more to it than that! Perhaps Bohr and Heisenberg are playing it *too* safe. I like Einstein's response[4,12] to the Copehenhagen interpretation,

> "I do not believe, however, that so elementary an ideal could do much to kindle the investigator's passion from which really great achievements have arisen. Behind these tireless efforts of the investigator there lurks a stronger, more mysterious drive: it is existence and reality that one wishes to comprehend."

Perseverance: Indeed Einstein has a very good point. The advancement of physics and the which have interacted strongly in the past. For the purpose of future discussion in this paper, we now introduce the wave function;

$$|\Psi\rangle = 1/\sqrt{2}(|+ -\rangle - |- +\rangle)$$

If the spin of the first particle is measured along an axis chosen to be *a*, then by the laws of quantum mechanics, we will always get the result of $s_a = \pm 1/2$. If we also measure the spin of the second particle along axis *a*, by the laws of quantum mechanics, it will *always* give us the opposite value. This means that no matter the distance separating the particles, whenever we measure the spin of one of them along a designated axis, we can conclude that the measured spin of the other one will always give us the opposite value along the same axis. EPR saw the greater implications of this phenomena in the context of the quantum theory, and they stated in their paper,[5,4,1]

> "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this quantity."

Immediately after the first measurement, this element exists, before any signal traveling with a velocity less than that of light has been able to reach the location. Einstein's locality postulate, based on his laws of relativity, asserts that a measurement at some point in space can help us to find out about the real features existing at some distance Δx, but it cannot modify them before the time $\Delta x/c$ needed for light to cover that distance. Now if we apply this postulate and say that measurement #1 can have no effect on measurement #2, and vice versa, then we can conclude, like EPR, that the elements of reality, associated with the spins for both particles, exists before all measurements. If we extend this argument to include the aspects of position and momentum, it then seems that there are elements of reality determining a definite value for both the position and the momentum of the particles. However, the Heisenberg uncertainty principle in quantum mechanics prevents us from describing a particle with definite values of both position and momentum. Hence we see why EPR conclude[5],

> "We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete."

Curiosity: But do not some people still maintain that the description is complete? How about

Bohr?

Perseverance: Throughout his life, Bohr held fast to the idea of "Complementarity;" one can know either the position or the momentum of a particle at an instant in time, but one cannot know both. Bohr's comment[6] on the proposed EPR paradox was,

> "From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by EPR contains an ambiguity as regards the meaning of the expression, 'without in any way disturbing a system.' Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical state of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system.* Since these conditions constitute an inherent element of the description of any phenomenon to which the term 'physical reality' can be attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete."

Curiosity: So Bohr refers to some type of an "influence" which must result from an action at a speed greater than that of light. Suppose we adhere to Einstein's locality postulate, based on relativity, which asserts that there can be no influence that is propagated faster than light. Is there some type of resolution to this apparent paradox?

Perseverance: Yes, there is a resolution in which we introduce the concept of the hidden variable. The motivation for the introduction of this concept was the belief that the motion of individual systems is strictly deterministic at a more profound level[4,13]. With the presence of hidden variables, one can think of quantum theory as being analogous to statistical mechanics which yields only average values of measured quantities.

Curiosity: But wait, along those lines of reasoning, one could then suppose that there are laws governing these hidden variables, and then maybe these laws, in turn, are merely average values of measured quantities. . . And could we not continue to extend this argument ad infinitum, to suit all of our needs? Do you really believe that the universe may be founded upon an infinite array of turtles[2] stacked upon each-others backs? Do you believe hidden variables *really* exist?

Perseverance: To this day, the best resolution to the questionable existences of hidden variables and faster than light influences lies in the form of Bell's inequality[7,8,1]. Bell formulated elegant, yet simple mathematical proofs demonstrating two statements[8,13,4]:

1. Einstein's locality postulate imposes constraints on the predictions of spin correlations in the form of inequalities.

2. The predictions of quantum theory for the EPR-Bohm experiment violate these inequalities implied by Einstein's locality.

Curiosity: So basically Bell calculated the probabilities of particular spin correlations according to the local hidden variable theory, and then compared those probabilities to the calculated probabilities of particular spin correlations according to quantum theory?

Perseverance: Correct.

Curiosity: And he found that the two different methods of predicting probability were in disagreement? This I have to see!

Perseverance: Very well then, let us proceed with a mathematical representation of Bell's inequality, demonstrating the conflicting predictions of Quantum theory and hidden variable theory[9,10].

<u>Quantum Probability</u>

We return to the system introduced earlier containing two spin 1/2 particles, in the isotropic singlet (zero net spin) state,

$$|\Psi\rangle = 1/\sqrt{2}(\,|+\,-\rangle - |-\,+\rangle)$$

Suppose that these particles separate, and we, the observers, choose to measure the component of the spin of particle 1 along an axis a, and we measure the component of spin of particle 2 along axis b, which is offset from axis a by an angle θ_{ab}. By the laws of quantum mechanics, a statistical correlation for the measurement of the two individual spin components along the two directions a and b exists. To satisfactorily treat the derivation of this probability, we momentarily turn to the laws of quantum mechanics:

Let us consider a single spin 1/2 particle. A complete set of orthogonal eigenvectors can be written as:

$$|+\rangle, \quad |-\rangle$$

These are the eigenvectors of the spin operator s_z, and they have eigenvalues $\pm\hbar/2$. By the completeness assumption, any state vector can be written as a linear combination of the above basis.

$$|\Psi\rangle = |+\rangle\langle+|\Psi\rangle + |-\rangle\langle-|\Psi\rangle$$

First we concern ourselves with particle 1. We want to find the eigenvector with eigenvalue +1, which corresponds to a positive spin in the z direction. Utilizing the Pauli spin matrix representation for σ_z, one gets;

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad ; \quad \det \begin{pmatrix} 1-\lambda & 0 \\ 0 & -1-\lambda \end{pmatrix} = 0 \ ; \lambda = \pm 1, \text{ we want } \lambda = 1, \text{ so; } \Psi_{z+} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

And because $\sigma_z\Psi_{z+} = \Psi_{z+}$, we see that Ψ_{z+} is indeed the desired eigen-vector.

Now let us concern ourselves with particle 2. Again we want to find an eigenvector with eigen-value +1, but this time the +1 corresponds to a positive spin along the direction of the b axis. The Unitary operator which rotates a state $|\Psi\rangle$ by an angle θ about the **x** axis is

$$U_x = \exp(-i\theta s_x/\hbar) = \exp\,(-i\theta\sigma_x/2) \text{ where } s = (\hbar/2)\sigma.$$

σ is the Pauli spin matrix representation of the spin operator, and because the Pauli spin matrices satisfy the identity $\sigma_a^2=1$, when we expand U_x in a series, all even powers of s_x will be the identity, and all odd powers of s_x will merely be s_x. We remember that the even powers of a series expansion add up to the cosine term, and the odd powers add up to the sine term. We can then write:

$$U_x = \exp\,(-i\theta\sigma_x/2) = \cos(\theta/2) - i\sigma_x\sin(\theta/2)$$

We wish to rotate the state Ψ_{z+} about the x axis by the angle $-\theta_{ab}$, so we operate on it with the unitary rotation matrix.

$$|\Psi_{b+}\rangle = U_x\Psi_{z+} = (\cos(\theta_{ab}/2) - i\sigma_x\sin(\theta_{ab}/2))\Psi_{z+} = \begin{matrix}\cos(\theta_{ab}/2)\\ i\sin(\theta_{ab}/2)\end{matrix}$$

$$\text{or, } |\Psi_{b+}\rangle = \cos\theta_{ab}\,|+\rangle + i\sin\theta_{ab}\,|-\rangle$$

The component of the Pauli Spin vector matrix along axis b is simply;

$$\sigma_b = \sigma\cdot\mathbf{b} = \sigma_z\cos\theta_{ab} - \sigma_y\sin\theta_{ab}.$$

To assure ourselves that $|\Psi_{b+}\rangle$ is indeed an eigenvector of σ_b with eigen-value +1, we operate on the eigenvector with σ_b.

$$\sigma_b|\Psi_{b+}\rangle = \begin{pmatrix}\cos\theta_{ab} & -i\sin\theta_{ab}\\ i\sin\theta_{ab} & -\cos\theta_{ab}\end{pmatrix}\begin{pmatrix}\cos(\theta_{ab}/2)\\ \sin(\theta_{ab}/2)\end{pmatrix} = \begin{pmatrix}\cos(\theta_{ab}/2)\\ \sin(\theta_{ab}/2)\end{pmatrix}$$

And we see that $|\Psi_{b+}\rangle$ does indeed represent a state in which the spin measured along the b axis will be $+h/2$.

Bell's theorem deals with two interacting spin 1/2 particles, so we now extend what we know about single particles to the case of two particles. The spin operators belonging to different particles commute, and the total spin operator for the system, s, is the sum of the individual operators for the two particles:

$$\mathbf{s} = \mathbf{s}(1) + \mathbf{s}(2)$$

We can divide the observables into two sets of completely commuting observables. From these two sets we are able to construct two different representations. The two sets are;

$$\text{set } A: \quad s(1)^2,\ s_z(1),\ s(2)^2,\ s_z(2)$$
$$\text{set } B: \quad s^2,\ s_z,\ s(1)^2,\ s(2)^2$$

A complete set of eigenstates for the set A, containing the observables $s_z(1)$ and $s_z(2)$, is $|m_1,m_2\rangle$ with eigenvalues $m_{1,2}h/2$ and $m_{1,2} = \pm 1$. We can represent these states with the following notation;

$$|+\ +\rangle\ \ |+\ -\rangle\ \ |+\ -\rangle\ \ |-\ -\rangle$$

A complete set of eigenstates of set B can be represented by;

$$|s,\ m\rangle, \quad \text{where } -s \le m \le -s$$

Because of completeness, we can write each of the eigenstates of set **B** as a linear combination of the eigenstates of set **A**:

$$|s,\ m\rangle = \sum |m_1,m_2\rangle\langle m_1,m_2|s,\ m\rangle$$

In this thought experiment, we concern ourselves with two interacting particles such that they are in an eigenstate of total angular momentum with **s** = 0. An intuitive way to get this state, $|s{=}0,m{=}0\rangle$ is to begin with $|s{=}1,m{=}1\rangle = |+\ +\rangle$, and operate on it with the lowering operator $s_- = s_-(1) + s_-(2)$. We then get;

$$|s{=}1,m{=}0\rangle = (s_-(1)+s_-(2))\,|m{=}+,m{=}+\rangle = (1/\surd 2)(|+\ -\rangle + |-\ +\rangle)$$

We know that the state we are seeking, $|s{=}0,m{=}0\rangle$, is orthogonal to $|s{=}1,m{=}0\rangle$, which means that the inner product must be zero. For this reason, we consider the state;

$$|\Psi\rangle = (1/\surd 2)(|+\ -\rangle - |-\ +\rangle) = |s{=}0,m{=}0\rangle$$

We can ascertain that this is indeed an eigenstate of total angular momentum with **s** equal to zero by operating on it with s_+ and s_-.

$$s_+(|+ -\rangle - |- +\rangle) = (|+ +\rangle - |+ +\rangle) = 0 \; ; \quad s_-(|+ -\rangle - |- +\rangle) = (|- -\rangle - |- -\rangle) = 0$$

And by the triangle rule we see that since *m* can neither be raised nor lowered, s must be equal to zero.

The laws of quantum mechanics allow us to imagine the simultaneous measurements of one component of the spin of particle 1 and one component of the spin of particle 2, because the spin operators for the two particles commute. For particle 1, we choose to measure the spin along the *a* axis, which is oriented in the +**z** direction. For particle 2, we choose to measure the spin along the *b* axis, which is rotated by an angle θ_{ab} with respect to the *a* axis (See Figure 2). We wish to compute the probabilities for possible results along these different axes, so we need the simultaneous eigenstates of $s_z(1)$ and $\mathbf{b}\cdot s(2)$. Specifically, we wish to find the probability that the spin of particle 1 measured along axis *a* is +1/2 *and* the spin of particle two measured along axis *b* is +1/2. We seek the eigenstate in which both single particle eigenstates have eigenvalues of +h/2.

Our plan is to start with the eigen-state in which both particles have a positive spin along the z axis, $\Psi_{z++} = |m_1{=}+, m_2{=}+\rangle$, and rotate the state of the second particle by the angle θ_{ab} so that it has a positive spin along the **b** axis. In this situation, the unitary rotation matrix operator only affects the second particle, so we write,

$$|\phi\rangle = U_x(2)\Psi_{z++} = (\cos(\theta_{ab}/2) - i\sigma_x(2)\sin(\theta_{ab}/2))\,|+ +\rangle$$

The calculations are analogous to the ones performed earlier for the single particle, and we get;

$$|\phi\rangle = \cos\theta_{ab}\,|+ +\rangle + i\sin\theta_{ab}\,|+ -\rangle$$

The quantum-mechanical probability amplitude for finding that the measurement of the spin of particle 1 along the *a* axis is +h/2 *and* finding that the measurement of the spin of particle 2 along the *b* axis is +h/2 is just the inner product of the eigenstate $|\phi\rangle$ with the singlet state $|\Psi\rangle$. Because of orthogonality, all the terms go to zero except for $\langle + -|i\sin\theta_{ab}|+ -\rangle$, and we find;

$$\langle\phi|\Psi\rangle = \langle + - | i\sin\theta_{ab} | + - \rangle$$
$$\langle\phi|\Psi\rangle = i/\sqrt{2}(\sin\theta_{ab})$$

And the probability is just the absolute value of the square of this amplitude, so,

$$P_{++} = (1/2)\ \sin^2(\theta_{ab}/2) = P_{--}$$

This is also the probability that the measured values of the spin components of the two particles will both be negative. These are the results obtained using pure quantum theory.

<u>Hidden Variable Probability</u>

We now introduce the concept of the hidden variable. We represent the probability with which a specific combination of results occurs for the two particles as

$$P = P(\ s_a(1),\ s_b(1),\ s_c(1);\ s_a(2),\ s_b(2),\ s_c(2)\ )$$

We can consider the hidden variables to be pre-set in such a way that a measurement of a particular system would give us (− + − ; + − +). By the laws of quantum mechanics, whenever particle 1 has a + component along a certain axis, particle 2 must have a − component along that same axis, and vice versa. This leaves us with eight symbols which have a non-zero probability.

Let us examine a small thought experiment, in which we compare the theoretical predictions of quantum theory with that of the hidden variable theory. We have three pairs of detectors depicted in Figure 1. In the middle of the detectors, we have a source of strongly interacting particles which are in the singlet state. When they separate, they are still in the singlet state, and particle **1** interacts with a detector on the left, while particle **2** interacts with a detector on the right. In this way, we observe the correlations between measured spins. Detector **1a** is set up to count the number of times particle **1** passes through it with a positive spin, $s_a = +h/2$. Detector **2b** is set up to register the number of times particle **2** passes through it with a positive component along the *b* axis, which we remember is rotated by an angle θ_{ab} with respect to axis *a*. We run this experiment and record the results for a large number of particles.

Spin Correlation Thought Experiment

Two interacting particles separate, and particle 1 is detected by detectors on the left, while particle two is detected by detectors on the right. The particles with positive components of spin oriented along a detector's set measuring axis will be counted by that detector.

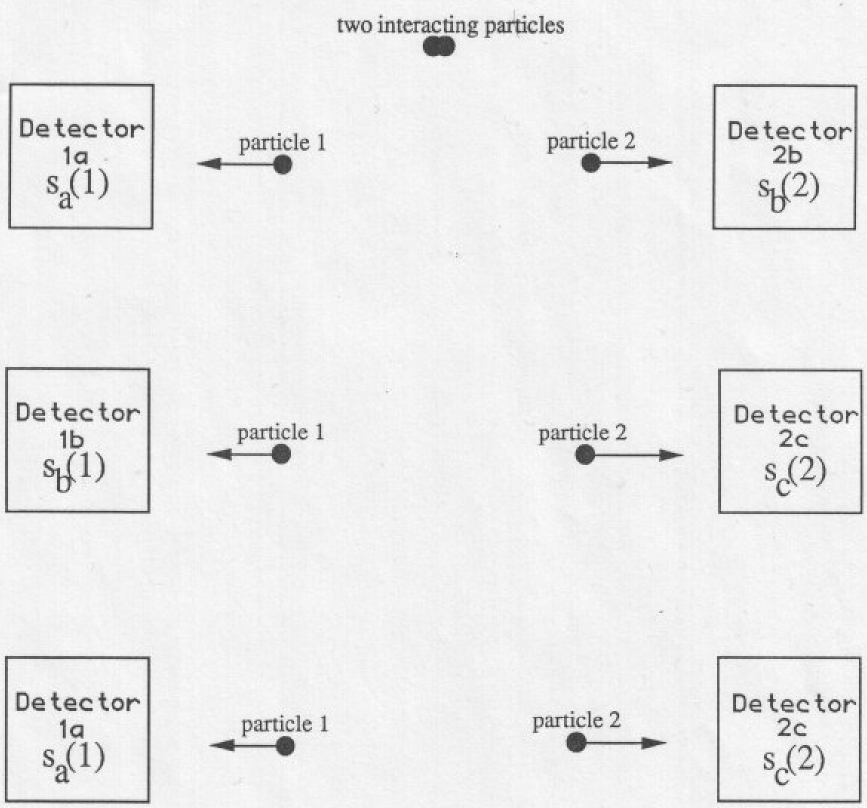


Figure 1

$\theta_{ab} = \theta_{bc} = \pi/3$ and $\theta_{ac} = 2\pi/3$, then,

$$\sin^2(\pi/6) + \sin^2(\pi/6) \geq \sin^2(\pi/3)$$
$$1/2 \geq 3/4$$

And we see that there is a contradiction!

Curiosity: So it seems that we must either abandon our view that there is an objective reality, or we must reject Einstein's postulate of locality[12,4]! What should we do? This paradox is like a bolt from the blue[1]!

Perseverance: That is a debate which is continuing as we speak. Many people have different opinions as to what we should do. Some, like John Bell, are leaning a little towards the idea of giving up locality[3];

> "Well, you see, I don't really know. For me it's not something where I have a solution to sell! For me, it's a dilemma. I think it's a deep dilemma, and the resolution will not be trivial; it will require a substantial change in the way we look at things. But I would say that the cheapest resolution is something like going back to relativity as it was before Einstein, when people like Lorentz and Poincare thought there was an aether. . ."

Curiosity: But what about the theory of relativity? We have a tremendous amount of experimental proof to support it. Doesn't this faster than light correlation violate relativity?

Perseverance: Because no signal is being sent, I can't really say this correlation violates the laws of relativity, but it is interesting to note that Einstein based his locality assumption upon his theory of relativity[4]. John Bell asserts that[3],

> "behind the apparent Lorentz invariance of the phenomena, there is a deeper level which is not Lorentz invariant. . . what is not sufficiently emphasized in textbooks, is that the pre-Einstein position of Lorentz and Poin-care, Lamor and Fitzgerald was perfectly coherent, and is not inconsistent with relativity theory. The idea that there is an aether, and these Fitzgerald contractions and Lamor dilations occur, and that as a result the instruments do not detect motion through the aether -- that is a perfectly coherent point of view."

Curiosity: Interesting! So there may be some type of aether after all! . . . How do others account for this correlation?

Perseverance: In the 1950's David Bohm[4,3,1] constructed a deterministic hidden variable model which exactly reproduced the predictions of quantum theory. Bohm and others have introduced varying versions of such concepts as the quantum potential, but I am not sure if anyone has successfully accounted for these faster than light influences, other than just saying that they exist. Perhaps that is all that one wishes to do. It is interesting to note the EPR argument was originally intended to characterize the short-comings of the orthodox Copenhagen interpretation of quantum theory, but one might say that it has become a message that an alternative theory describing reality would have to include faster than light influences[4]. A new theory of physical reality will have to reside within a context in which faster than-light influences make sense.

III. Delayed Choice

Curiosity: It seems the more I find out in this game, the less I know for sure. . . Another thing that is starting to bother me is that, we, the observer, seem to play a roll in the outcome of an observation depending upon what we choose to measure, or the questions we choose to ask. In Bell's thought experiment described above, my choice to measure a certain aspect of a particle seems to irreversibly effect what we can say about the other one. There seems to be something funny going on. . . Am I imagining all this?

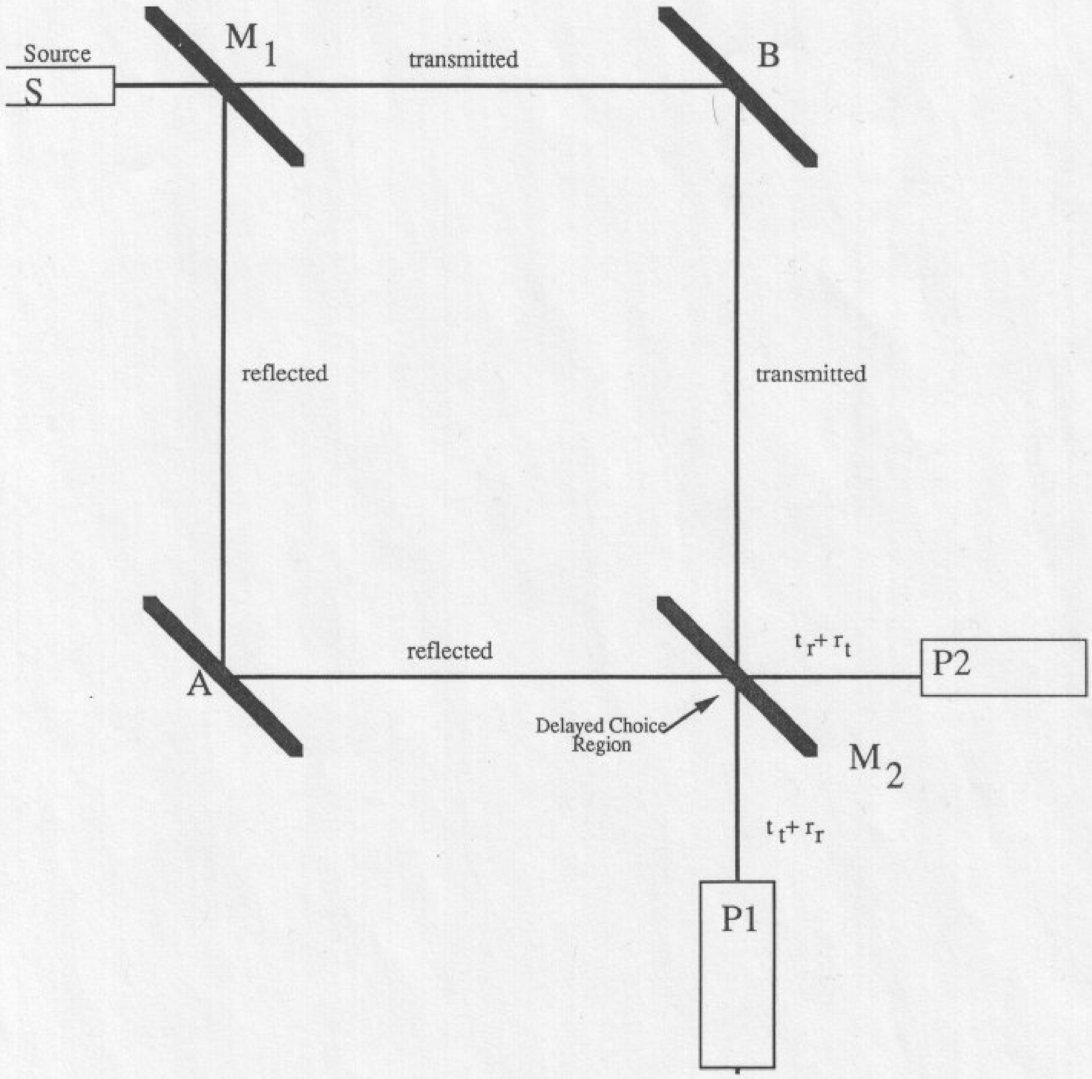
Perseverance: I don't think so. John Archibald Wheeler[1,2,11], who agrees with Bohr in rejecting the existence of atomic reality independent of man and his observations[11], has devised a "delayed choice" experiment in which the following becomes apparent,

> "a choice made in the here and now has irretrievable consequences for what one has the right to say about what has *already* happened in the very earliest days of the universe, long before there was any life on earth."

Curiosity: Are we once again encountering these mysterious actions at a distance? But now they span over time too?

figure 3:

DELAYED CHOICE EXPERIMENT



Perseverance: It would seem so. . . let us turn to Figure 2. A source S of extremely low intensity emits photons. This source is so low that we can assume it emits one photon at a time. There is a long interval between one photon and the next, and the light is incident upon a half-silvered mirror M_1, and it is divided into two parts. The reflected part, denoted by **r**, is again reflected by a totally reflecting mirror A and sent towards the photo-multiplier P_2. The transmitted part, denoted by **t**, is reflected by the fully reflecting mirror B and sent towards the photomultiplier P_1. Now I ask you, suppose we run a photon through the experiment. Where would you expect to see it counted?

Curiosity: Since the photon is a fundamental particle, and it cannot be split, and it would be counted by either P_2, or P_1.

Perseverance: Correct. I assume your answer is the same as saying that you would expect a single photon would follow either path **r***A***r** or path **t***B***t**, but never both paths? Is it not?

Curiosity: Yes, I believe it must follow one path or the other.

Perseverance: Very well then, it does indeed seem that this demonstrates the corpuscular behavior of photons. However, suppose we introduce a second semi-transparent mirror M_2, shown in Figure 2, into the experiment. We call the location of this mirror the delayed-choice region (DCR). Because of the different indices of refraction for glass and air, we know that we can choose the thickness of M_2 in such a way that the superposition of the transmitted part of $\mathbf{r}(\mathbf{r}_t)$ and the reflected part of $\mathbf{t}(\mathbf{t}_r)$ generate destructive interference, or a wave of zero intensity. The exact thickness can be calculated as a function of the wavelength. This time, where do you suppose a photon will be detected?

Curiosity: It seems to me that all the photons will be detected by $\mathbf{P}_1$, for as you have demonstrated, $\mathbf{P}_2$ receives only destructive interference. . .Wait, this is suggesting that a photon can be split! That it has wave-like properties! Can a single photon interfere with itself?

Perseverance: From experiments conducted by Carrol Alley and his colleagues at the university of Maryland[3], it appears so. So once again, I ask you, which path did the photon follow?

Curiosity: In order to interfere with itself, the photon must have traveled both paths, but then it cannot be an unsplittable, localized particle! So depending on whether or not we include M_2 in the experiment, it seems that we can actually affect which path or paths the photon follows! We affect whether the photon behaves like a wave or like a particle!

Perseverance: Yes indeed, now Wheeler has taken this a step further in the proposition of his Delayed Choice experiment. In this version, a second half-silvered mirror M_2 can be inserted or excluded at the last instant, after the photon has already interacted with M_1 and is propagating along path **r** and/or **t**. What do you suppose would happen if we inserted M_2 at this last instant?

Curiosity: I would have to say that the photon interferes with itself, but then are we not affecting what has happened in the past? We influence what the photon has done, after it has already supposedly done it! This would seem to contradict the familiar rules of causality!

Perseverance: Yes it would, in some contexts of thinking, but Wheeler reminds us of Bohr's context[3],

> "In actuality, we have no contradiction. As Bohr said, we have no right to talk about what the photon is doing during its long travel from the point of entry -- from the first half-silvered mirror to the point of registration. After all, no elementary quantum phenomenon is a phenomenon until it is measured."

Curiosity: I hear what Bohr is saying, but all the same, there does seem to be some backwards causality. We, the observers, appear to affect the reality we observe, depending upon what we choose to measure! But here again I return to my original question. What makes us conscious observers?

Perseverance: I hesitate to draw the line between the observer and the observed, because as Bohm points out[3], they are both made of the same substance. Some regard an observation as being the result of an irreversible act of amplification, such as a photon blackening a grain on photographic film. However, Wigner holds the view that the elementary quantum phenomenon process, such as a blackening of a grain, does not really happen unless it enters the consciousness of an observer. Wheeler also regards an irreversible amplification as being only half of the two stage observation process[3], but his view differs slightly from Wigner's. He explains[3],

> "Wigner speaks of the elementary quantum phenomenon as not really having happened unless it enters the consciousness of an observer. I would rather say that the phenomenon may have just happened but may not have been put to use. And it's not enough for just one observer to put it to use -- you need a community."

Curiosity: Is there no objective reality? Does all reality arise from our observations?

Perseverance: As I have already expressed, I am not sure what reality is, for it seems that it is many different things to many different people, all operating in different contexts. Even words such as "objective" and "subjective" used to describe reality can take on different meanings depending upon the immediate context in which they are used. On the matter of whether or not reality already exists independent of our observations, David Bohm says[3],

> "I've already put myself between Einstein and Bohr. I say there is an area where our observations do create reality, as in human relationships: when people become aware of each-other and communicate they create the reality of society. But I think that the universe as a whole does not depend on us to do that."

Here Bohm is speaking of "our observations," in the context of human relationships. As human beings, we must communicate to survive, and it is useful to define concepts such as mind and observation. However, in the contemplation of existence itself, these concepts seem to evaporate. Bell[3] tells us that,

> "The problem of measurement and the observer is the problem of where the measurement begins and ends, and where the observer begins and ends. Consider my spectacles, for example: if I take them off now, how far away must I put them before they are part of the object rather than the observer? There are problems like this all the way from the retina through the optic nerve to the brain and so on. I think, that -- when you analyze this language that the physicists have fallen into, that physics is about the results of observations -- you find that on analysis it evaporates, and nothing very clear is being said."

Curiosity: Surely there must be a difference between the consciousness observer and the system being studied!

IV. Wigner's Friend:

Perseverance: I want to say that there is, because I *am* conscious, but there is the unavoidable dilemma of where to draw the line separating the observer and the observed. "Wigner's Friend"[9,10] is a good illustration of this dilemma. Suppose that Wigner's Friend, Mr. Observer, can be put in a pure state, with quantum numbers A representing a state of readiness to observe the particle. The system, consisting of a spin 1/2 particle, can also be put in a pure state, with quantum number a representing the z component of the spin. We can then represent the state vector for the particle plus Mr. Observer as:

$$|\Psi\rangle = |A,a\rangle$$

The expectation value of any function F of observables of Mr. Observer is independent of the quantum numbers a of the system to be observed:

$$\langle F\rangle = \langle A,a|F|A,a\rangle = \langle A,b|F|A,b\rangle$$

At this point in time, because the expectation values of all functions F of the observer are independent of the quantum number a of the system, Mr. Observer does not know what state the system is in.

We now proceed to describe the time evolution via the Hamiltonian. Before Mr. Observer "looks" at the particle, he and the particle are *not* coupled. This means that the Hamiltonian is the sum of two terms, one consisting only of observables of Mr. Observer, the other consisting only of observables of the system:

$$\boldsymbol{H} = \boldsymbol{H}_{Mr} + \boldsymbol{H}_s$$

Observables for Mr. Observer and the system commute, so we know $\boldsymbol{H}_{Mr}$ and $\boldsymbol{H}_s$ commute. The time translation operator, $U = \exp\,(-iHt/h)$ can then be written as the product;

$$U = U_{Mr}U_s; \text{ where } U_{Mr} = \exp\,(-iH_{Mr}t/h), \text{ and } U_s = \exp\,(-iH_st/h)$$

At a time t after the start of the experiment, before Mr. Observer looks at the system, the state vector is $U|A,a\rangle$, so the expectation value of the function F of Mr. Observer is;

$$\langle F\rangle_t = \langle A,a|U^{\dagger}FU|A,a\rangle = \langle A,a|U^{\dagger}_{Mr}FU_{Mr}|A,a\rangle$$

The middle expression follows because U_s commutes with F. The final expression is the expectation value of the function of observables for Mr. Observer, and we remember that it is independent of a. Therefore, the expectation value $\langle F\rangle_t$ at time t of any function of Mr. Observer is independent of a. In this immediate situation, Mr. Observer does not yet know the state of the system.

Now let us suppose Mr. Observer observes the system. The particle and Mr. Observer become coupled, and the Hamiltonian is no longer a sum of separate functions of the observables of Mr. Observer and the system. A correlation now develops between the particle and Mr. Observer, and $\langle F\rangle$ depends on a. If we consider the Stern Gerlach experiment, we can visualize a situation in which an observation does not affect the state of the system, (see Figure 4). Suppose a particle entered the SG apparatus with spin down. If Mr. Observer so happened to be observing the upper arm, he would see no particle and he could assume that a particle with spin down passed through the apparatus. Similarly, if the spin of the particle in the system were up, $a = +$, and Mr. Observer so happened to be observing the lower arm, he wouldn't see any particle, and he would be able to conclude that the spin was up, $a = +$, at the end of his observation. Half the time Mr. Observer chooses to observe the upper arm, and the rest of the time he chooses to observe the lower arm.

Mr. Observer walks away from the system, and the coupling is thereby terminated. Suppose the initial state of the system was an eigenstate of the spin operator s_z with eigenvalue +h/2, and the initial state vector was $|A,+\rangle$. The final state vector would be $|A_u,+\rangle$, where A_u represents the state of Mr. Observer after he has discovered that the spin is up. Similarly, if the initial spin were down, the initial state would be $|A,-\rangle$ and the final state would be $|A_d,-\rangle$, where A_d represents the state of the physicist on learning that the spin is down.

Now suppose that the particle is initially in a state which consists of a linear combination of spin up and spin down,

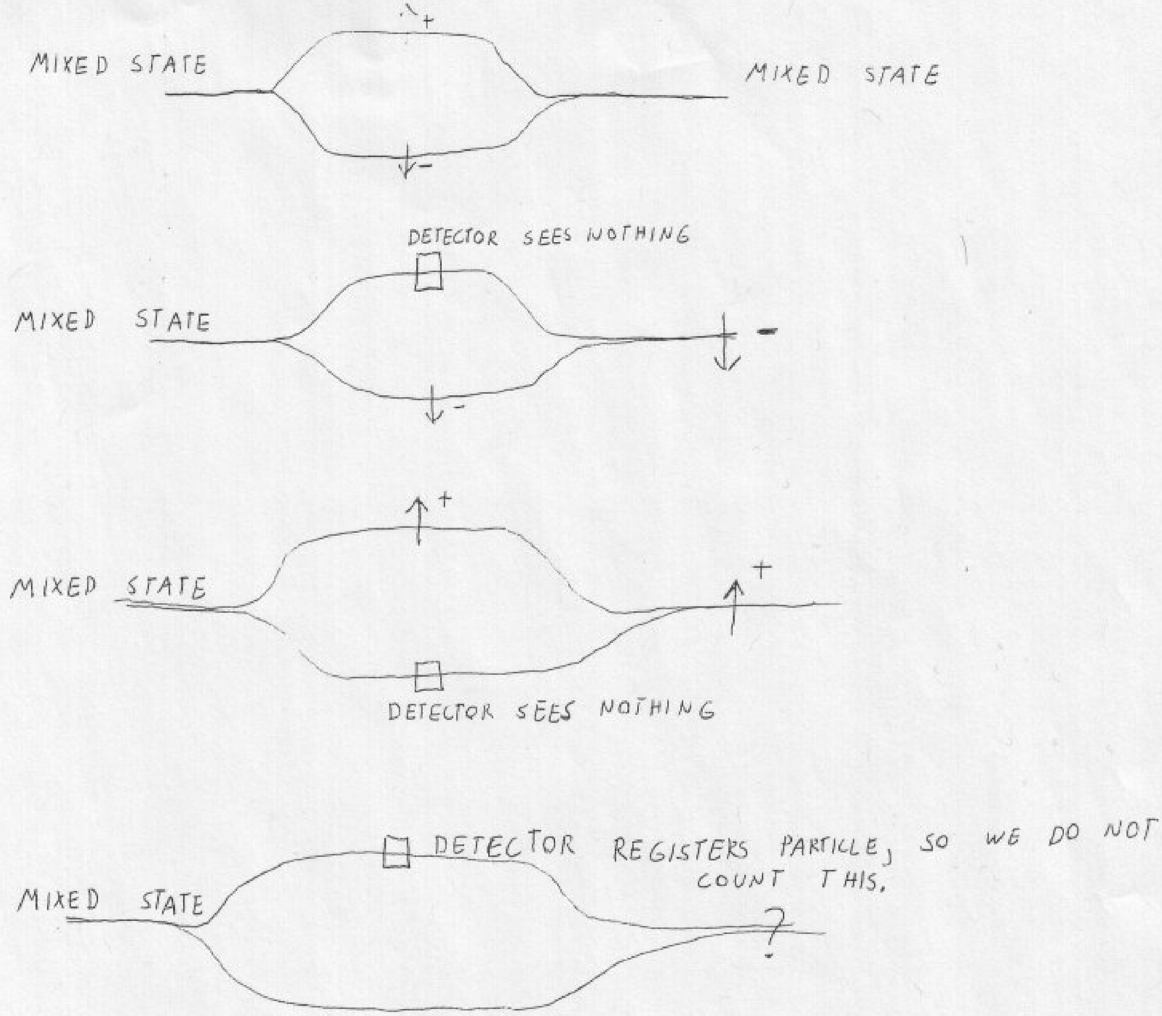

MIXED STATE
MIXED STATE
DETECTOR SEES NOTHING
MIXED STATE
MIXED STATE
DETECTOR SEES NOTHING
DETECTOR REGISTERS PARTICLE, SO WE DO NOT COUNT THIS.
MIXED STATE

FIGURE 4.

$$|\Psi_i\rangle = \alpha\,|A,+\rangle - \beta\,|A,-\rangle)$$

We remember that Mr. Observer is originally in the state *A*, with no knowledge of the system. Mr. Observer takes a look at the particle, and he then walks away from it at a time t_f later. What, I ask you, is the final state after the physicist and the particle have separated?

Curiosity: Because of the linearity of Schrodinger's equation, I would have to say that the final state would be;

$$|\Psi_f\rangle = U(t_f)\,|\Psi_i\rangle = \alpha\,|A_u,+\rangle - \beta\,|A_d,-\rangle)$$

But wait! It appears that Mr. Observer exists in a linear superposition of two states! If I were Mr. Observer, I would most certainly know whether the spin is up or the spin is down! What is happening here?! When does an observation become an observation? When it enters the mind? Whose mind?

V. Conclusion:

Perseverance: Very good question, but I am not sure how to answer it. John Bell[3] expresses this dilemma well,

> "I am a professional theoretical physicist and I would like to make a clean theory. And when I look at quantum mechanics, I see that it's a dirty theory. The formulations of quantum mechanics that you find in the books involve dividing the world into an observer and an observed, and you are not told where that division comes. . .You're not told about this division between the observer and the observed. What you learn in the course of your apprenticeship is that for practical purposes it does not matter where you put this division; that the ambiguity is at a level of precision far beyond human capability of testing. So you have a theory which is fundamentally ambiguous, but where the ambiguity involves decimal places remote from human abilities to test. . ."

Curiosity: But is it not true that one might also say, in a Bohr's context, that quantum mechanics is an extremely good theory as far as predicting events goes?

Yes! It is quite true that quantum mechanics is an excellent theory!

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