CHASING THE QUANTUM DRAGON

An Introduction to “Quantum Weirdness”

W.H. Madden

To Casey, my wife, for all her patience and support.
And to my late friend, Bob D…who *listened*.

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INTRODUCTION TO PART 1

> “*Anyone not shocked by quantum mechanics has not understood it*.”
>
> —Prof. Niels Bohr, one of the founders of Quantum Mechanics

ABOUT THE TITLE: When asked about the mysterious processes going on between direct observations of a single quantum ‘entity’ (such as a photon or electron), the eminent physicist John Wheeler likened it to a “Great Smoky Dragon” (Wheeler was not only an extraordinary physicist—he had a way with words, too. He was the first to coin the term “black hole”).

I’ve used Wheeler’s metaphor as the framework for this book.

It’s not really a book about quantum mechanics (QM) theory at all. Instead, it’s about the implications and consequences of QM: what it can—and *cannot*—tell us about the nature of physical reality. And, although written at an introductory level, with a minimal amount of math, this is not an *easy* book…because the topics discussed are, in themselves, not easy…

A WORD ABOUT QUANTUM MECHANICS: Let’s be very clear on something, right here at the beginning: the experimental predictions of Quantum Mechanics have—so far, at least—always been *right*. *Always*. For over 100 years, the theory has been tested, tested, and re-tested. No matter how bizarre or counter-intuitive its predictions, QM has proved to be experimentally correct. Of course, this doesn’t necessarily mean the current version of QM will be the *final* version of the theory…but, to date, it's the best one we've got.

That's one of the great things about science in general (and physics in particular). Unlike art, literature, philosophy, or politics, in physics, *experiment* is the final judge of a theory's worth. Promising ideas may arise, and, depending on popularity, aesthetics or personalities, go in and out of fashion. But, when all is said and done, it's the hard truths coming out of the laboratory that determine which theories stay, and which ones go.

Besides being right, QM is *useful*: it has given us personal computers, smart phones and flat-screen TVs. It has helped us understand chemistry and radioactivity, the inner workings of stars, and the structure of DNA. It has given us remarkable new tools for medicine, science, technology, and war. It has even given us ways to— perhaps—understand the birth and fate of the Universe itself.

So, what's the problem?

Simply this: QM predicts many strange and counter-intuitive things, but it is stubbornly silent about the underlying *physical* nature of the world. It is this peculiar silence that leaves room for some of QM's outrageously bizarre interpretations… interpretations so strange, in fact, that even the founders of the theory, at one time or another, agonized over its meaning.

QM theory is both highly formalized and highly abstract. *Formalized* because it is so deeply rooted in mathematics, and—as with all things mathematical—subject to the tightest possible constraints. *Abstract* because there are elements in the theory that are not easy to interpret, in terms of physical reality. Yet the theory, as a whole, is remarkable in its ability to *predict* experimental outcomes, as has been demonstrated, time and time again.

WHO THIS BOOK IS FOR:

Readers seeking a concise, general overview of the *concepts* of quantum "weirdness"—an overview without too much math, scientist biographies, entertaining anecdotes, or a detailed history of QM theory itself.

Readers who would like to "get behind" such attention grabbing headlines as "Experiments Show Single Particle in Two Places at Once", "Teleportation Achieved in the Lab" or, more sensationally, "Can Quantum Mechanics Prove ESP Exists?"

More knowledgeable readers—including, hopefully, professional scientists and engineers—who, through long exposure, have perhaps become *too* familiar with the theory, and have forgotten just how *strange* the quantum world appears to those unacquainted with it.

WHO THIS BOOK IS *NOT* FOR:

Readers from the "Shut Up and Calculate" school of thought. There's absolutely nothing wrong with this attitude—in fact, it's very sensible. After all, why look a gift horse in the mouth? QM theory *works*, and most practicing physicists are too busy putting it to good use to worry overly much about *why* it works. Most of this book, though, is concerned with non-practical questions regarding QM—specifically, what is the theory *telling* us about the nature of physical reality?

Sophisticated readers who've already made up their minds on the subject, and no longer wish to discuss it. There are many interpretations of QM currently available, each markedly different from the next, and numerous physicists—and non-physicists—have embraced one or another of these as being the best way of looking at QM. (We'll talk briefly about some of these interpretations later, and discuss the good—and 'bad'—

features of each). This book approaches the various types of “quantum weirdness” with an open mind, as topics still open to debate.

So-called “Quantum Mystics”, who seek a link between ancient Eastern philosophies and modern physics; also, those who look to QM for some kind of validation of paranormal phenomena (ESP, precognition, telekinesis, etc.) *Maybe* there’s some truth to such things, and *maybe* QM has something to do with it all, but I doubt you’ll find what you’re looking for in here.

In the following pages, we’re going to examine—very closely—two “showpiece” quantum experiments, and some of their variations.

The first example we’ll use is the double-slit interference (“DSI”) experiment, which is so simple a very basic version of it can be performed at home. In fact, the original, low-tech DSI experiment was first carried out by the English physicist Thomas Young back in 1803, using ordinary *sunlight* as his illumination source.

The second example is a version of the famous Einstein-Podolsky-Rosen (“EPR”) experiment, which requires much more sophisticated equipment…but the *results* of this experiment are pretty straightforward. It is the *interpretation* of these results which has given rise to so much controversy.

As always, in the end, it is the experimental results that count. Throughout this book, the experiments are described *first*, along with their results. The interpretations will be saved until after.

This book is written as an introduction to various examples of “quantum weirdness” for non-specialists, *by* a non-specialist. I strongly encourage all interested readers to “second source” the information provided here.

The Internet is good for that sort of thing, but it can be both a blessing and a curse. It's a vast resource for valid, authoritative information…but, since it's open to all, it can also be a swamp of pseudo-scientific nonsense.

Do a basic Internet search for "quantum mechanics" and you'll get, literally, *millions* of results. Narrowing the search down to "Interpretations of Quantum Mechanics" will still return several thousand hits. Be *very* discriminating. Stick to sites like arXiv.org (which has pre-prints of papers by academic researchers), or sites that end in .edu (denoting educational institutions), so you'll find dependable results, not wild speculations. Wikipedia is great on some topics, so-so on others. An *outstanding* site for beginners is hyperphysics.com, which has introductory through advanced pages on all things physics.

A bibliography is included at the end of this book, listing introductory, intermediate, and advanced texts for those who'd like to delve more deeply into the subject.

In Part 1, we'll look at the work done by the professional physicists—their experiments, their results, and their interpretations. Since Part 1 is intended as an introduction *only,* it contains just a bit of very basic algebra.

In Part 2, I'll offer my own speculations on the topics discussed in Part 1. If nothing else, I promise you a few interesting and unconventional ideas. There's *some* unavoidable math contained in Part 2, but nothing more difficult than high-school algebra, geometry, and trigonometry…with just a dash of calculus thrown in.

I recommend reading this book in one of three ways: read Part 1 by itself if you're just looking for an informal introduction to QM "weirdness". Skip straight to Part 2 if you're already *thoroughly* familiar with the double-slit interference experiment, various forms of the “EPR” experiment, and the more “mainstream” interpretations of QM theory. Read both Parts 1 and 2 if you, like me, find the content in Part 1 to be a little too…*strange*.

CHAPTER 1

THE DRAGON'S EYES: WAVE/PARTICLE DUALITY

> "*You know the double slit experiment? It's like that.*"
>
> —Nobel Prize winning physicist Richard Feynman, whenever asked about some counter-intuitive result in QM.

Let's follow Professor Feynman's advice, and start by looking at the double-slit interference (DSI) experiment—the one you can do at home. (Detailed instructions for simplified, "at-home" versions of this experiment can be found on the Internet…do a search for "*home quantum experiments*").

Like many people encountering descriptions of this simple experiment for the first time, I simply didn't see any *problem* at all. After a little thought, though, I got it…

As Professor Bohr had promised, I was *shocked*. This was *crazy*, and it made no *sense*. The real world couldn't possibly be this *weird*.

And yet, this simple experiment proves that it is…

Description of the DSI Experiment:

Three things are all that's required for this experiment:

1. A bright source of light (typically, laser light is used as the source).

2. An opaque screen with two very narrow, parallel slits cut closely together (the “slit-barrier”).

3. A screen on which to observe the results after the light has passed through the slits.

The light source is directed through the slit barrier, and, some distance away—say 1 meter or so—we observe what happens on the screen. See Figure 1.1 for a schematic illustration of the DSI experiment. The figure is *not* drawn to scale. A typical example of a “table-top” DSI experiment might have the following parameters: each slit is .1 millimeter wide, the two slits are separated by 1 millimeter, the slit barrier to screen distance is 1 meter, and the source wavelength (for, say, a commercially available red laser pointer) is 630 nanometers.

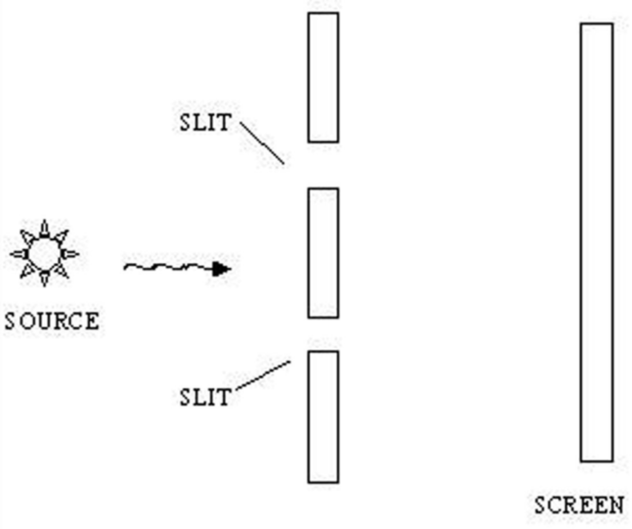

FIG. 1.1 The Double Slit Interference Experiment.

First, let both slits be blocked. *Nothing* is seen on the screen. A trivial step, perhaps, but an important one, because it demonstrates a crucial point: *something* is going from the source to the screen. When both slits are blocked, that *something* is blocked, too.

Next, let just one of the two slits be opened. On the screen, we see a "smur" (my wife's charming term for a *smear* and a *blur*) of light, brightest in front of the opened slit, and fading symmetrically off to either side. Not too surprising—it's about what you might expect.

(Actually, I'm oversimplifying here. If you look *really* closely, you'll see the "smur" pattern is composed of faint light and dark bands. For now, though, let's just stick with the "smur" idea; this *single-slit diffraction* pattern will be addressed later, in Chapter 9).

Just to be thorough, let's block that first slit, and unblock the other one. Again, no surprise…the single-slit "smur" pattern re-appears.

Now comes the interesting part. If we unblock *both* slits, we might expect to see two single-slit "smur" patterns. Instead, we get a series of light and dark bands (called *fringes*) on the screen, with the brightest of these at the center. The fringes fade off symmetrically to either side—and this is the *double-slit interference pattern*. See Figure 1.2.

(For the *example* parameters listed above for a "typical" DSI experiment, the spacing between the centers of the bright fringes is about .63 millimeters…so, the first fringe appears about .63 mm from the middle of the central, brightest fringe, the second fringe appears at 1.26 mm, the third at 1.89 mm…etc.).

FIG. 1.2
The Double Slit Interference Pattern

When Thomas Young first saw a form of this pattern back in 1803, he took it as *proof* of the wave nature of light, because a wave-based model of light gives exactly these results.

A WORD ABOUT WAVES:

Waves are of great interest to physicists, because they appear so often in the natural world. Pressure waves in the air are what we hear as sound. Earthquakes come in waves, as do tsunamis. The Scottish physicist James Clerk Maxwell first realized light itself is an electromagnetic wave, back in the 1860's.

Waves can behave in interesting ways, all of which are well understood. In fact, mathematically speaking, *all* waves have several features in common.

You don't need to be a physicist to get a good feel for wave behavior, though…just take a stroll along a seaside beach on a calm summer's day.

Walking along the section of beach exposed to the open ocean, you see waves rolling in. Each wave has a certain height (the wave's *amplitude*), the wave crests are a certain distance apart (the *wavelength*), and so many waves come in per minute (the wave *frequency*).

As you come to a protected harbor, there's a man-made seawall, some distance out in the water, running parallel to the beach. The seawall is there to block the waves, so small boats can approach the shore safely. To handle boat traffic on busy days, the seawall has two gates, which can be opened or closed independently.

When both gates are closed, *no* waves reach the beach.

When only one gate is opened, each incoming ocean wave must squeeze through that narrow opening, then fan-out as it continues towards shore.

With both gates opened, each incoming wave is divided into two parts, with each part fanning out, both racing towards the beach. (See Figure 1.3, below).

When the two component parts of the original ocean wave intersect at the shore, the *resultant* wave is much higher at some points along the beach, and much lower at others. In wave mathematics, this is called *interference*. In Figure 1.3, the white lines represent the wave *crests,* and the black lines represent the wave *troughs*. Where two white lines intersect, the resultant wave height (that is, the wave *amplitude*) will be at a maximum… and this is called *constructive interference*. Where two black lines intersect, the resultant wave amplitude will be at a minimum—called *destructive interference*.

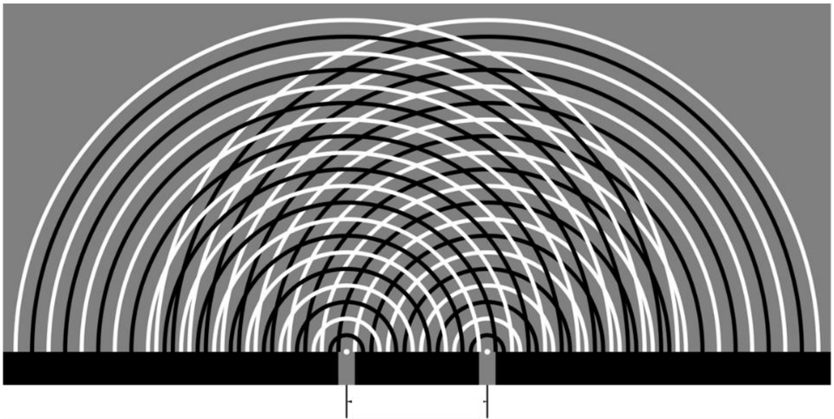

FIG. 1.3 The Wave Model of the DSI Experiment

But, enough digression; let’s get back to the DSI experiment.

The next test involves dimming the intensity of the laser source way, way down, by passing the beam through a series of stacked filters, *before* the beam reaches the slit barrier. As the beam is passed through more and more filters, it becomes dimmer and dimmer, and so does the interference pattern on the screen. When the beam becomes *extremely* faint, a point is reached where only one bright spot at a time ‘flashes’ on the screen. Each of these point-like flashes represents the absorption of an individual photon—something like a single “piece” of light—at the screen…and that’s not very wave-like at all.

This next part may be beyond the casual home experimenter, but it has been done in the lab. The screen is replaced with, say, a strip of photographic film, and the experiment is continued, still using a very, very faint beam. The photographic film allows us to record the build-up of the resulting pattern on the screen, single photon by single photon, over time.

When only one slit is open, our familiar single-slit “smur” pattern builds up over time. *But, when both slits are opened, the* *double-slit interference pattern builds up over time…even though just one photon at a time is being recorded.*

And that's the shocking part.

If we assume the laser beam is composed of individual, "particle-like" photons, we'd expect each photon to pass through just one slit *or* the other. But, if this is the case, how does each individual photon "know" whether to contribute to the single-slit "smur" pattern, or to the double-slit interference pattern? In other words, how can each photon "know" the state—opened or closed—of the slit *it did not pass through?*

On the other hand, if we assume the laser beam is composed of waves, why is it that, at this *very* low intensity, the light is *always* detected as single, point-like flashes on the screen…just like a particle?

When both slits are open, ask yourself this innocent question: *What goes through the slits*?

Clearly *something* does, because, when both slits are blocked, *nothing* is seen on the screen.

This *something* cannot be a "conventional" wave, because, at very low intensities, we observe single, point-like flashes on the screen. An ordinary wave—say, a single ripple in a pond—simply doesn't *do* that. The entire ripple doesn't *vanish* when one part first touches the edge of the pond.

Until actually *observed* on the screen, though, our *something* seems to possess just the wave-like attributes needed (amplitude, wavelength, and interference) to *exactly* account for the banded, double-slit interference pattern we see build up on the screen …one "flash" at a time.

But our *something* cannot be a “conventional” particle, either. An ordinary particle should pass through just one slit or the other, *always* contributing to a single-slit “smur” pattern, and *never* contributing to an interference pattern.

Without fail, though, our *something* always appears as a single, point-like flash on the screen…just like we’d expect from a particle.

The double-slit interference experiment vividly demonstrates the phenomena of *wave/particle duality*…our first example of “quantum weirdness”.

Let’s make matters even more confusing. If we somehow *monitor* the two slits, we find each individual photon *does* pass through only one slit *or* the other, and *never* through both, just as we’d expect a particle to do. But, when we monitor the slits in this way, the wave-like interference pattern on the screen *disappears*.

If we know *which* slit the photon went through, we no longer have an interference pattern to explain!

The nature of our mysterious *something* seems to depend on the type of experiment we perform: if we look for a wave, we find a wave. And, if we look for a particle, we find a particle.

What is going on here?

Nature itself, as revealed through experiment, behaves in this way. Quantum mechanics successfully *describes* this surprising behavior, but does not really *explain* it.

So, what *does* QM theory have to say about all this?

Unfortunately, not much.

One of the early forms QM took was as a wave-based theory—developed by the Austrian physicist Erwin Schrödinger. Initially, Schrödinger conceived of his waves as being physically *real*.

Actually, Schrödinger's main concern was with constructing a theory of the atom consistent with the known physics of the time. His model dealt primarily with the nature of electrons, not the nature of light. However, his reasoning applied to both. Schrödinger pictured the single electron in a hydrogen atom as a kind of pulsating, three dimensional "charge cloud" surrounding the nucleus. But when Schrödinger extended his model to the *two* electrons found in the helium atom, he realized that a *six* dimensional "charge cloud" was required; for the *three* electrons in the lithium atom, a *nine* dimensional charge cloud was needed, and so on for each of the higher chemical elements. This representation by "higher-dimensional" waves led physicists to question the *physical reality* of Schrödinger's "charge cloud" concept.

Soon after, the German physicist Max Born interpreted Schrödinger's "waves" as waves of *probability*: abstract mathematical constructs which, until they interact somehow with the "real world", have no concrete *physical* interpretation. Specifically, Born related the absolute value of the *square* of the amplitude of the probability wave at any point in space to the *probability* of finding the electron at that point. This probability interpretation (known as the "Born Rule") applies not only to electrons, but to *all* other quantum 'entities'—like photons, protons, neutrons, atoms, etc.—as well.

(Sophisticated readers might protest this as being an over-simplification, but—for our purposes—it will do).

So, even after 300+ years of investigation by some of the brightest people in the world, physics can accurately predict what light will *do*, but can't really explain what light *is*.

Perhaps light itself is just *different*, somehow? After all, it is pretty ethereal stuff. What if we repeat our DSI experiment, using something more substantial? How about a beam of electrons, for instance?

Electrons, you'll recall from high school science, are part of atoms. And you and I—and pretty much everything else we see in the world—are *made* from atoms.

Electrons are very nicely standardized. *Every* electron is identical to every other electron. All electrons have the same charge, and all electrons have the same mass. (Early experiments by the English physicist J.J. Thompson first measured the charge to mass *ratio* of what were then termed "corpuscular cathode rays". Building on this work, the American physicist Robert Millikan, in 1913, published research in which the *charge* of the electron was accurately determined, thus allowing him to deduce the electron's *mass*. For details, search for "Millikan's Oil-Drop Experiment" on the Internet).

Electrons, it would seem, are pretty substantial things. Yet, if the DSI experiment is done using electrons instead of photons, we get the same results:

When one slit is open, the "smur" pattern is seen on the screen.
When both slits are open, the banded, double-slit interference pattern is seen.

Even when the "beam" consists of just one electron at a time, the appropriate pattern still builds up, depending on whether one or both slits are opened. (See Image 1, below.)

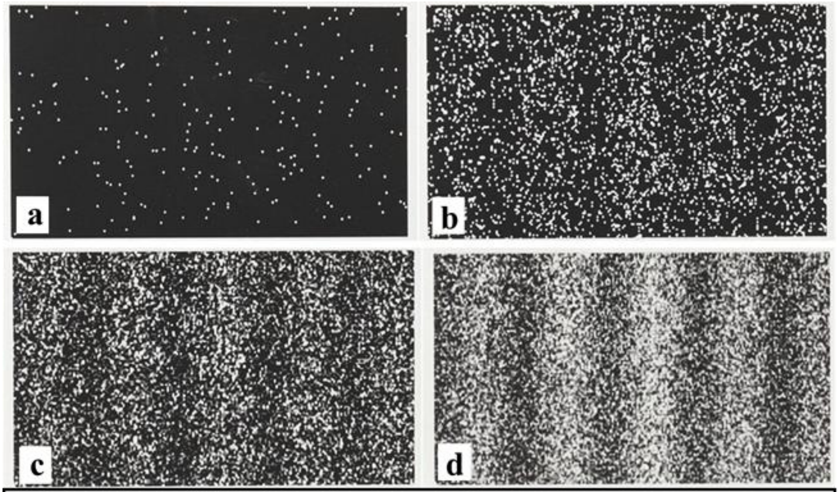

IMAGE 1 The Build-Up of the DSI Interference Pattern

Image 1 comes from an actual experiment performed by the Japanese physicist Akira Tonomura and colleagues, working at Hitachi Labs, in 1989. In this elegant experiment, Dr. Tonomura succeeded in recording the *build-up* of the DSI interference pattern…*one electron at a time*. Image 1a shows the pattern after 200 electrons have passed through the double- slit barrier; Image 1b, after 6000 electrons; Image 1c, after 40,000 electrons; and Image 1d, after 140,000 electrons. Note that any given *single* electron *might* be detected anywhere on the screen—but, for the interference pattern to build up, each electron shows a *tendency* to appear in one of the interference fringes. This “build-up” of the double-slit interference pattern is also what would be seen if individual photons were used, instead.

What if our beam is made up of something even *larger*? The DSI experiment has been performed with certain kinds of atoms, and even sizeable molecules. When both slits are open, the double-slit interference pattern still builds up…*even with one particle at a time*.

Once more, we come back to our innocent question: *what goes through the slits*?

Since formal QM theory can't directly answer this question, we must conclude that, even when dealing with such "familiar" things as electrons, atoms, and molecules, physics can tell us what they will *do*, but not really what they *are*.

If the DSI experiment is performed with something *macroscopic*— say, the stream from a water hose, or the spray from a sandblaster—we no longer get an interference pattern. *Why not*?

Streams of water are composed of individual droplets, and sandblaster sprays are made of individual grains of sand. But, in turn, *these* things are made from molecules and atoms and electrons. What, then, is the "magic" size—the dividing line between the *micro* and *macroscopic* worlds?

Back in 1905, Albert Einstein was the first to thoroughly describe light in terms of particle-like "light quanta" (some years later, in 1926, the term "photon" was coined by two other scientists). Essentially, Einstein showed that an apparently wave-like phenomenon (like light) must sometimes be treated in a particle-like fashion (as photons). For his work on the "Photo-Electric Effect", Einstein received a Nobel Prize.

Then, in his 1924 doctoral thesis, the French physicist Louis de Broglie turned Einstein's idea on its head. *If waves could be treated as particles,* asked de Broglie, *why not also treat particles as waves*? (de Broglie won a Nobel Prize for his work, as well).

De Broglie showed that every moving particle has an associated *wavelength*, inversely proportional to the particle's mass and velocity. De Broglie's idea was later confirmed by two American physicists, C.J. Davisson and L.H. Germer, working at Bell Laboratories. In their experiment, when a beam of particle-like electrons was sent through certain types of mineral crystals, the electrons exhibited wave-like behavior…exactly confirming De Broglie's predictions.

When this "de Broglie wavelength" is *large* in comparison to the particle's size, the particle can behave like a wave. Moving droplets of water, or moving grains of sand, have vanishingly *small* wavelengths in comparison to their size, and so do *not* exhibit noticeable wave-like behavior. Molecules, atoms, and electrons, on the other hand, can be made to have relatively *large* wavelengths in relation to their size, so their wave-like behavior becomes apparent.

The "de Broglie wavelength" is—mathematically speaking—very precisely defined: it is inversely proportional to the particle's *momentum* (momentum being the product of a particle's *mass* multiplied by its *velocity*). The de Broglie wavelength appears again and again throughout quantum mechanics…but what could possibly be the *physica*l meaning of a *particle's* "wavelength"?

Physicists have differing views of this question, but no one consensus opinion.

Two other experiments help to emphasize the essential *weirdness* of wave/particle duality. The first of these is a demonstration of *single photon interference*. (See Figures 1.4a and 1.4b, below.)

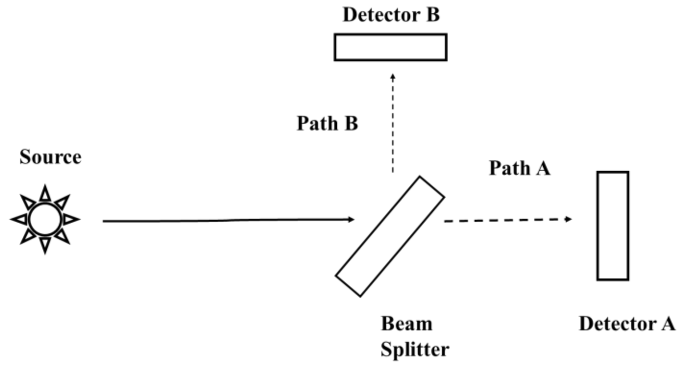

FIG. 1.4a The Single Photon Interference Experiment

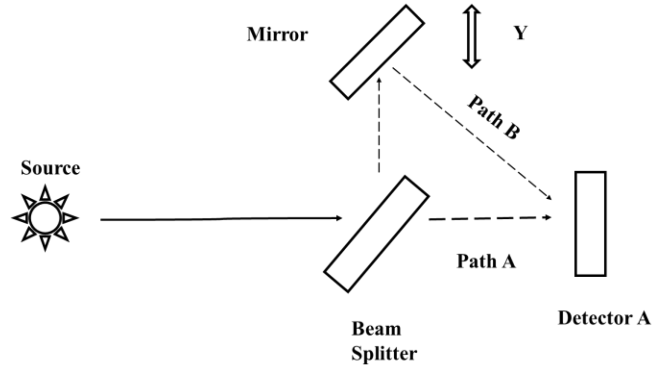

FIG. 1.4b The Single Photon Interference Experiment

Once again, the illumination source is a severely attenuated laser beam, so that—on average—only one photon at a time is present in the apparatus. This attenuated beam is first sent through a "beam splitter"—essentially, a half-silvered mirror. The beam splitter randomly permits *about* half the photons to pass straight through it, and randomly deflects *about* half the photons in the direction shown. If we place photon detectors at the two positions illustrated in Figure 1.4a, each individual photon registers at *either* detector A *or* detector B…but *never* at both. Each individual photon, it seems, follows *either* path A *or* path B to the detector…just like we'd expect a particle to do.

Next, we replace detector B with an ordinary mirror, angled as shown in Figure 1.4b. The position of this mirror can be adjusted at will up or down in the vertical direction, Y. What will detector A register now?

As the mirror's position is varied slightly up or down, the number of photons registered at detector A also varies. When the mirror is placed at some positions, *many* photons are detected in a given amount of time…but, at slightly different positions of the mirror, very *few* photons are detected. It's as though each *individual* photon—somehow—follows *both* paths through the beam splitter, then interferes with *itself*.

Just as in the DSI experiment, if we can determine *which* path the photon takes (by deploying *both* detectors A *and* B), each photon obligingly follows a single path—*either* path A *or* path B. But, if we *cannot* determine which path is taken (by substituting a mirror for detector B, and observing *only* the results at detector A), the photon seems to follow *both* paths A *and* B.

An even more striking experiment was performed by the physicists R.L. Pfleegor and L. Mandel in 1967. In their "Two Source" interference experiment, two *independent* lasers were aimed at a single detector, with a very small angle between the two separate beams. (See Figure 1.5, below.)

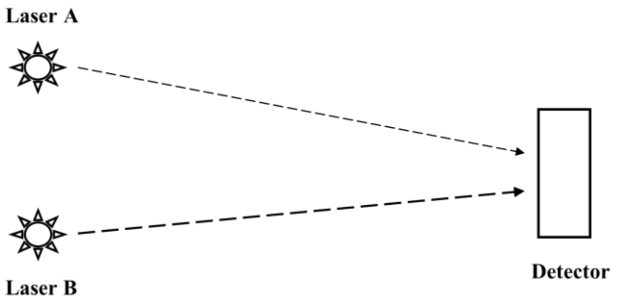

FIG. 1.5 The Pfleegor-Mandel Experiment

Now, ordinary sources of light (such as two sunbeams, for example, or the beams from two flashlights) will *not* interfere with each other; two such beams of ordinary light will pass right through one another, with no interaction at all. But laser light is *different*…it is composed, as physicists would say, of *coherent* light. Regarded as a wave, all the wave crests and troughs in a beam of coherent light are "lined up", which is one of the reasons why laser light is so powerful.

Two identical lasers, aimed at a common target, will, very occasionally, become coherent *with* one another (at least for very short times—the so-called *coherence time*)…and interference *between* the two beams becomes possible.

In the Pfleegor-Mandel experiment, the light from *each* laser is again extremely attenuated, so that—on average—only one photon at a time registers at the detector. During the brief coherence times, strong evidence for single photon interference was observed.

Of course, we cannot *know* from which laser each *individual* photon came, but the point here is that, for interference to occur, that single photon seems to have followed *both* paths—from two *distinct* sources—to the detector.

In turn, this must mean—in some sense, at least—*the single photon was co-produced by both lasers.* In the Pfleegor-Mandel experiment, there's not a *single* source producing a *single* photon which, by somehow following two paths, interferes with itself. Instead, there are two *distinct* sources, and two *distinct*, direct paths to the detector…yet single photon interference is still observed.

The English physicist P.A.M. Dirac (who, among other achievements, first proposed the existence of anti-matter) once stated that *a photon can only interfere with itself…*a statement directly confirmed by the single-photon interference experiment, but one that is somewhat problematic in light of the Pfleegor-Mandel "Two-Source" experiment.

For a *truly* weird example of photon interference, see Appendix A—which describes the "Quantum Eraser" experiment. Before doing so, however, please read the sections on photon polarization (see Chapters 5 and 10), to fully appreciate the implications of this experiment.

The purpose of this chapter has been to show just how *strange* the world all around us really is. Wave/particle duality is present *everywhere* in the everyday world in which we live.

And it's still an open question as to "*what goes through the slits*."

The Quantum Dragon's eyes, it would seem, see the world in two *very* different ways.

CHAPTER 2

THE DRAGON’S SCALES: HEISENBERG’S UNCERTAINTY PRINCIPLE AND THE END OF DETERMINISM

> “*I cannot believe God plays dice with the Universe.*”
>
> —Albert Einstein

Just prior to Schrödinger’s working out of his wave-based model of quantum mechanics, the German physicist Werner Heisenberg had taken a more abstract, purely mathematical approach. During development of his so-called “matrix mechanics”, Heisenberg discovered a remarkable thing: between certain pairs of *attributes* (for example, position *and* momentum…energy *and* time…etc.) there exists an absolute *minimum* of uncertainty. The more *precisely* you know a particle’s position, Heisenberg found, the *less* you can know about its momentum. As a particle’s position is measured more and more accurately (and nothing in QM theory prevents us from doing so), the *uncertainty* in its momentum increases towards infinity… and vice-versa.

For example, consider the position of a freely moving particle in space. The particle’s position can be described in terms of three components: its left/right position (along the ‘*x’* axis), its up/down position (along the ‘*y*’ axis), and its back/forth position (along the ‘*z*’ axis).

Likewise, the particle’s total *momentum* (that is, the particle’s *mass* multiplied by its *velocity*) can also be described using the x, y, and z components of the particle’s motion. Heisenberg found that the uncertainty relationship between position and momentum applied only to *each* of these three components. If, say the particle's 'x' position is known *exactly*, the 'y' or 'z' components of the particle's momentum could also be measured *exactly*…but the momentum component in the 'x' direction *cannot*.

Conversely, if the particle's *momentum* component in the 'x' direction is measured *exactly*, its *position* in the 'y' and 'z' directions can be measured exactly…but its 'x' position *cannot*.

However, to *exactly* specify a particle's position in space, all *three* position components (in the x, y, *and* z directions) must be specified *exactly*. And, to completely describe a particle's motion, all three momentum components (again, along the x, y, and z directions) must be known…*exactly*.

In other words, if you know *exactly* where a particle *is*, you'll have no idea where it's *going*, or how fast it will get there.

And, if you know *exactly* how fast a particle is moving, and in which direction, you'll have absolutely no idea where it *is*.

Roughly speaking, this is why, if we know *which* slit a photon has gone through (so we know about where it *is*), the accompanying increase in its momentum uncertainty (where it is *going*) ruins the interference pattern in the DSI experiment.

This is also why you must say farewell to that picture of the atom you first learned in high school. You know the one: electrons circling in tidy orbits around a central nucleus. At atomic scales, Heisenberg's Uncertainty Principle renders even the *idea* of exact trajectories meaningless, let alone the picture of well-behaved electron orbits.

(Questions regarding the concepts of position and motion are not new…in fact, they have a long, illustrious history. As early as the 5th century B.C, the Greek philosopher Zeno of Elea proposed a series of problems regarding the nature of motion, known as

“Zeno’s Paradoxes”. One of these—“the Arrow Paradox”—seemed to demonstrate that an arrow, shot from a bow, could not really be said to *move*.

Zeno argued as follows: at any time during its flight, the arrow obviously has a position in space. But, by definition, motion means a *change* in position with time. So, if the arrow has a definite *position*, it cannot really be said to be moving. Conversely, if the arrow is *moving*, it cannot be said to have a definite position.

Of course, Zeno knew the arrow actually *did* move…he’d never willingly place himself between an archer and the target. Zeno’s aim was to show that “common sense” notions about the nature of motion could lead to logical contradictions.

It wasn’t until the 17th century development of mathematical calculus, with its concept of *instantaneous* velocity—defined as an *infinitesimal* change of position divided by an *infinitesimal* interval of time—that Zeno’s Arrow paradox was finally resolved).

Heisenberg’s Uncertainty Principle re-opened questions regarding position and motion. The *quantum* uncertainty described by Heisenberg is completely unlike the *classical* uncertainty we are used to in our everyday world. There, uncertainty in measurement is most likely due to poor instruments, sloppy procedure, or both. The idea behind classical uncertainty of this kind is that, although we may currently be unable to measure something exactly in *practice,* in *principle,* at least, we could.

A common misconception regarding Heisenberg’s Uncertainty Principle is that it arises from the *interaction* of the measuring method with the thing being measured. As an example, one way to take the temperature of a glass of water is to immerse a thermometer in the glass. But the thermometer itself, having a temperature of its own, might then *change* the temperature of the water.

To find the position of a single electron, we must first "bounce" at least a single photon off of it. But the photon, having an energy of its own, will cause the electron to *recoil* to some degree or another—just like in a game of billiards. The more energy a photon has, the shorter its wavelength, and the better its "resolution"—that is, the finer the detail it can "see". (Early radar transmitters in World War II, for instance, used radio waves of comparatively *long* wavelengths, and so could only resolve large formations of incoming enemy planes. Modern military radars—using much *shorter* wavelengths—can "see" individual bees in a swarm).

This "interaction" idea isn't *wrong*, of course…the collision of a single photon with an electron will, in fact, cause both to recoil. The change in the electron's momentum depends on the energy—or, equivalently, the *wavelength*—of the photon used (this is known as the "Compton Effect").

But Heisenberg's Uncertainty Principle goes much deeper than this. Even in *theory*, there are certain pairs of attributes—such as position and momentum—that you can never *simultaneously* measure exactly, no matter how perfect your instruments, or how flawless your technique.

Consider, for example, placing a single electron in an imaginary, uncharged, one-dimensional 'box' (think of this 'box' as an *extremely* thin, hollow tube, sealed at both ends, so the electron is free to move only along the length of the 'box'). By confining the electron in this way, we've established its position as being *somewhere* inside the 'box'. The electron's *position uncertainty* then equals the length of the 'box'. According to Heisenberg, this very act of confinement *induces* an uncertainty in the electron's momentum.

Making the 'box' shorter and shorter (and so reducing the electron's *position uncertainty*) causes the electron's *momentum uncertainty* to get larger and larger. Note that *we're not directly interacting with the electron in any way*, yet, by changing the length of the 'box', we're changing the *uncertainty* in the electron's momentum.

Using a very short 'box' doesn't guarantee the electron's momentum will be very large… but it *could* be. As the 'box' gets shorter and shorter, the *range* of possible momentum values gets larger and larger.

QM can tell us the *probability* the momentum will be some value or another within this range, but that is *all* it can tell us…and we can never do better. This kind of *quantum* ignorance is what caused Einstein to make his famous comment about God, dice, and the Universe. Einstein sought a more fundamental theory—one that could replace the *probabilities* of QM with *definite* predictions.

Pre-quantum mechanics—what is now termed *classical mechanics*—had been on a tremendously successful roll, right up until about the end of the 19th century. Building on the mathematical work of Isaac Newton and others, physicists had unraveled all kinds of mysteries. The motions of the moon, planets, and stars could not only be understood, but very accurately *predicted*. Great progress had also been made in understanding electromagnetism and thermodynamics. Because of all these successes, a new kind of "world view" had developed among physicists—Newton's so-called "Clockwork Universe".

Imagine an omniscient being—God, if you'd like—who knew the position *and* momentum of *every* single particle in the

Universe at a given instant of time. Such a Being, in Newton's Clockwork Universe, could predict both the past *and* the future position and momentum of every galaxy, every star, every planet, and every atom. It was as though the entire Universe was some incredibly vast *machine*…a gigantic, extraordinarily complex mechanism ticking away. This idea—so intellectually appealing to physicists—was based on the concept of *determinism*.

In a game of billiards, when you hit the cue ball, you count on your shot producing a particular outcome. If you aim for a bank shot involving the eight ball, for instance, and you're reasonably good at the game, that's exactly what you'll get. Put another way, you're relying on the concept of determinism: if I hit the cue ball *so*, the result will be *this*.

Classical physics generalized this basic idea: *If the initial state of a system is known precisely, and all the forces acting on the system are also known precisely, we can predict all future states of the system precisely*.

In *practice*, of course, exact knowledge of *all* the initial conditions of a system would be nearly impossible to obtain…and the more complicated the system is, the more difficult this would be. Even the *slightest* inaccuracy in the initial measurements could lead, over time, to wildly divergent results.
(In modern mathematical *chaos theory*, this is referred to as *sensitivity to initial conditions*, and has been nicknamed the "Butterfly Effect": when predicting the weather, for example, even the best meteorological models can only forecast out for a limited time, because a lone butterfly flapping its wings in, say, Brazil, could lead, a week later on, to a typhoon in the Pacific).

Chaos theory acknowledges the practical difficulties in knowing—*exactly*—all the initial conditions. But, in *principle* at least, this could be done.

Quantum mechanics—and Heisenberg's Uncertainty Principle—say *no, this cannot be true*. Even in *theory,* we can never know *all* the initial conditions exactly. The best we can ever do is use QM to tell us the *probability* of a given outcome.

According to the Uncertainty Principle, classical determinism—at the quantum scale, at least—must be abandoned.

Armored beneath such scales, the true nature of the Quantum Dragon remains forever shielded.

CHAPTER 3

THE DRAGON’S SMOKE: SCHRÖDINGER’S CAT, “WIGNER’S FRIEND” AND THE COLLAPSE OF THE WAVE-FUNCTION

> “*Who watches the Watchers*?”
>
> —Ancient Roman proverb

Now, let’s get back to the DSI experiment.

We’ve established that *something* goes through the slits, and QM can tell us the probabilities of how this *something* will behave. But QM also tells us that, no matter how clever we are, the Uncertainty Principle forbids us from ever seeing that *something*—Wheeler’s “Great Smoky Dragon”—in its naked, wild state. If we can somehow determine which slit each photon passes through, the wave-like interference pattern disappears. If we can’t, the interference pattern will build up over time.

So, we’re still stuck with the question: *What goes through the slits*?

QM gives us—as a working answer, at least—something we *can* use as a ‘proxy’ for our elusive Dragon: the so-called “wave-function”, an abstract entity, a kind of “probability wave”, whose *mathematical* properties are very well understood. When this wave-function interacts with the screen, it somehow “collapses”, much like a soap bubble pops, and—*Presto*!—we see a single, point-like flash somewhere on the screen. The *probability* of seeing that single flash at some particular location on the screen is given by the “Born Rule”: it depends on the absolute value of the square of the amplitude of the wave-function at that location.

However, one of the central issues in the interpretation of QM theory is this: ‘*orthodox’ QM theory offers no mechanism for the ‘collapse’ of the wave function at all.*

To be a little more specific, in one form of ‘orthodox’ QM theory, the wave-function is described by what’s known as the *Schrödinger equation*. This is a well-behaved differential equation, whose mathematical properties are very clear cut. A key feature of this equation is that it *evolves* linearly over time…that is, the *solutions* of this equation change, depending on the specific values for the variables used (time, position, etc.)—but in a very predictable, definite way. The equation itself has, at any time, a *set* of solutions…and every one of these solutions is mathematically *valid*. Schrödinger himself referred to this aspect of his equation as a “*catalog of outcomes*”. But, when a measurement takes place (for instance, in the DSI experiment, when the wave-function of a single photon interacts with the screen) only *one* of the many *possible* outcomes is actually observed…with a probability given by the “Born Rule”.

In other words, the formal mathematics of QM theory does *not* tell us how the many *possible* outcomes described by the Schrödinger equation “collapse” into the one, single outcome *actually* observed in a given experiment. This ‘transition’ from many *possible* outcomes to just a single *observed* outcome has been variously called the “*quantum/classical boundary*”, the “*Heisenberg cut*”, the “*collapse of the state vector*”, or—in the terminology we’ve been using here—the “*collapse of the wave-function*”. Attempts to understand this ‘transition’—which has become known in QM as the “*Measurement Problem*”—are one of the reasons why so many different *interpretations* of quantum mechanics have been proposed.

Later researchers have called into question still other issues regarding the QM wave-function. Can it really be associated with a single *quantum* (such as a *single* photon, electron, or atom)?

Or, must the wave-function only apply to ensembles of *many* quanta? And, if this is the case, what is the minimum *number* of quanta required?

Consider, for a moment, Tonomura's DSI experiment with electrons, as described in Chapter 1. It's *true* that the "wave-like" interference pattern only becomes apparent after a fairly large number of electrons have been registered on the screen (refer back to Image 1). But, in the Tonomura experiment, the electrons are registered *one at a time*. If a wave-function is responsible for the interference pattern, *and* this wave-function *only* applies to an *ensemble* of particles, then this ensemble must consist of *individual* quanta—*spread out over time*.

In the Tonomura experiment, let's hypothetically suppose the electrons are registered at the *extremely* low rate of, say, one electron per second. The "wave-like" interference pattern in Image 1b is just barely discernible after about 6,000 electrons have been registered on the screen. If a wave-function is truly responsible for this "wave-like" interference pattern, *but* the wave-function only applies to *ensembles* of electrons, we're talking about a wave-function which persists—*presumably*—for 6,000 *seconds*…that is, 100 *minutes*, or a little over an hour and a half. Is this yet another manifestation of "quantum weirdness"?

Some researchers have gone even farther, suggesting there is but one, single, *universal* wave-function, which *never* 'collapses'. And this one "universal" wave-function describes—literally—*everything* in the Universe: *all* particles, *all* conceivable measuring instruments, and *all* possible observers… *including you and me*. (More on this in the next chapter, in the section on the "Many Worlds Interpretations").

For now, though, should we even bother to pursue our question—"*what goes through the slits?*"—any further? After all, at the macroscopic scale, quantum effects are so tiny as to be practically negligible, and the “weirdness” of the quantum realm cannot escape into our everyday world.

Or can it?

Seriously troubled by this question, and to call attention to the *strangeness* of QM’s implications, Schrödinger devised a clever thought experiment, one which seemed to show that “quantum weirdness” *can* leak out into our macroscopic, everyday world… and with very serious consequences, indeed.

Imagine a sealed container, within which are placed a cat, a source of radioactivity, a Geiger counter, and a vial of poison gas. The experiment is set up so that, if the Geiger counter clicks, a mechanism cracks the vial of gas open, and the cat is exposed to the lethal effects.

All QM can ever do is express the *probability* of the Geiger counter clicking within some allotted time. The simple question Schrödinger asked was this: *before we actually look, is the cat alive or dead?*

Expressed in quantum mechanical terms, we can derive a wave-function that tells us the *probability* the Geiger counter has clicked. Since the container is sealed, the only way to really *know* is to open it up, and look inside. When we do, the QM wave-function instantly ‘*collapses*’, and we’re greeted by either a very angry cat… or a very dead one.

But, before we look, the cat’s physical state (alive or dead) is described by the QM wave-function. Only the probability of one state or the other is known. According to QM, this *superposition of states* describes the *physical reality* of the cat; the cat must be regarded as both alive *and* dead (with various probabilities) until the sealed container is opened.

This isn’t a question of everyday, classical ignorance on our part, where common sense tells us the cat is either alive *or* dead, and we just won’t know until we look. The wave-function, if taken literally, says the cat is both alive *and* dead…until we ‘collapse’ it by actually *looking*.

Has the argument been pushed too far, leading to an absurd conclusion? Wouldn’t the cat, at least, know whether it’s alive, even *before* the container is opened?

Next, consider an extension of this thought experiment, first proposed by the physicist Eugene Wigner, and—appropriately enough—known as the “Wigner’s Friend” scenario. This time, both the cat in its container *and* the human observer are inside a closed laboratory, with no communications to the outside. When the first observer opens the cat’s container, the wave-function describing the cat’s state ‘collapses’, and the cat is observed as alive *or* dead. But what if a *second* observer—“Wigner’s Friend”—is waiting just outside the closed lab? For this second observer, *the wave-function has not yet collapsed…*and won’t until she either opens the door and sees for herself, or is told by the first observer how the cat is doing.

The “Wigner’s Friend” scenario can be extended indefinitely, by adding a third observer, and a fourth, and so on, and so on…

How literally should we take the wave-function now? And what, exactly, causes it to ‘collapse’? At what point does the *quantum* ignorance become *classical* ignorance? Does the Geiger counter ‘collapse’ the wave-function? The cat? The first observer? The second…?

According to QM, when both slits are opened in the DSI experiment, the wave-function passes through them *both*, interfering with itself much like an ordinary, physical wave, thus producing the interference pattern seen on the screen, so it seems pretty substantial indeed. If we change the *physical* setup of the experiment in some way—by changing the *slit barrier to screen distance*, for example—the interference pattern observed on the screen *changes*. If the *separation* between the two slits is varied, the interference pattern changes. If we change the color—that is, the *wavelength*—of the light used, the pattern changes… and so forth. This illustrates a crucially important point: the *physical* setup of the experiment can, apparently, *act* on the wave-function.

In the “Wigner’s Friend” scenario, though, the wave-function has ‘collapsed’ for the first observer, but still exists for the second observer, and so on, and so on...

Behind all the smoke, is there really a Quantum Dragon at all?

CHAPTER 4

THE DRAGON’S LAIR: THE MANY, MANY INTERPRETATIONS OF QUANTUM MECHANICS

> “*Three blind men, traveling down a road, come upon an elephant. The first man, feeling the elephant’s side, declares they have hit a wall. The second, feeling the elephant’s leg, thinks they have walked into a tree. The third man, feeling its trunk, fears they have stumbled across a snake.*”
>
> —Ancient Hindu Proverb

Observations, Theories, and Interpretations: We’ve all heard the story about Isaac Newton’s discovery of gravity, when an apple fell on his head. Besides being apocryphal, this story misses an important point. *Everybody* is familiar with gravity; we’re so used to it that the only time we really notice it is when something goes *wrong* (like when I’m up on a ladder, painting my house, and step back to admire my work).

An apple falling from a tree, the trajectory of an arrow or a cannonball, the beauty of a waterfall…all these are simply *observations* of the effects of gravity. What Newton was looking for was a way to answer very specific questions, and solve very definite problems: *How fast was that 6 ounce apple falling when it hit my head 3 feet above the ground, after falling 10 feet from a branch? How fast was it traveling when it was still 8 feet above the ground? How long would that apple have taken to hit the ground, had my head not gotten in the way?* And so forth.

Questions like these can only be answered by a *theory*—specifically, a *mathematical* theory—of gravity. To develop this, Newton first had to invent a mathematical framework—a tool, if you will—of tremendous power: the calculus.

Using his new theory, Newton could calculate the motion not only of falling apples, but also of the moon and planets. Later astronomers applied Newton's theory to actually *predict* the existence and position of a previously unknown planet—Neptune—discovered years after Newton's death.

Yet Newton's theory provided no clue as to what gravity actually *was*, and Newton himself was careful not to guess: "*Hypotheses non fingo",* said Newton ("I offer no hypotheses"). But the temptation was there, of course, and the theory cried out for some kind of *interpretation*…

To be taken at all seriously, any such interpretation had better *agree* with Newton's very successful theory. If it did not, it would be dismissed out of hand. More than two centuries later, Albert Einstein developed his own theory of gravity—General Relativity—that superseded Newton's. Einstein's theory *included* Newtonian gravity as a subset, and Einstein's theory, at last, told us what gravity actually *is*: the bending of space-time. In essence, said Einstein, gravity is *geometry*. No need for interpretations here; the theory itself says it all.

It's exactly the same with quantum mechanics. To be taken seriously, any interpretation had better be in complete agreement with the very successful mathematical theory. And, hopefully, it should attempt to offer at least some insight into QM's underlying *physical* nature.

Should the fact that there are so many interpretations available today make us wonder if current QM theory is the *final* version? As happens so often in the progress of science, will our *present* version of QM theory be replaced by a more 'comprehensive' theory…one needing no *interpretation* at all?

Maybe. And maybe not.

Let's now take a quick look at *overviews* of some current interpretations of QM theory. The brief survey below is, by no means, *complete*…there are so-called "minority" interpretations not mentioned at all. The idea here is to give the reader some sense of the variety of approaches being investigated. The interpretations aren't listed in any particular chronological order, either…instead, they've been *very* roughly grouped by category.

In the following descriptions, many of the more technical and mathematical aspects of these interpretations have either been *greatly* simplified, or, in some cases, entirely omitted. This simplification is quite deliberate, as much of the material lies well beyond the limited scope of this book—which is, after all, intended as an *introduction* only. "*The devil*," it's been said, "*is in the details*", but the brief summaries given below are primarily focused on seeing how each interpretation might answer our innocent question: "*In the DSI experiment, what goes through the slits*?"

THE COPENHAGEN INTERPRETATION

> "*Of that which we cannot speak, we must pass over in silence*."
>
> —Ludwig Wittgenstein,
> "*Tractatus Logico-Philosophicus*"

This interpretation, named after the city in which Niels Bohr was a professor, is probably the one most widely accepted by physicists today. It's also perhaps the most straightforward interpretation, and the most pragmatic. According to the Copenhagen Interpretation, *there is no "objective" quantum* *reality at all*. By this, of course, Bohr and his followers did not mean to deny the *existence* of quantum ‘entities’, like photons or electrons, atoms or molecules. What they *did* question, though, is whether such things could be regarded in the same way as ordinary, macroscopic objects, like apples or baseballs, which we’re familiar with in our everyday world.

For example, in the double-slit interference experiment, we saw how light acts like a *particle* when actually *detected* at the screen, but exhibits apparently *wave-like* properties (like interference) on its way *to* the screen.

One of the fundamental tenets of the Copenhagen Interpretation is the concept of *complementarity*: no experiment can *ever* reveal *both* the wave *and* particle nature of quantum ‘entities’ at the same time. If an experiment tests for particle-like behavior (by determining, for example, *which* slit the photon passes through in the DSI experiment), the wave-like behavior is obscured…and the interference pattern *disappears*. Conversely, if the experiment tests for wave-like behavior (by observation of the double-slit interference pattern, for example), the particle-like behavior is obscured…and we can no longer say *which* slit the photon has gone through.

According to the Copenhagen Interpretation, photons, electrons, atoms, etc., should *not* be considered as *either* particles *or* waves…although, depending on the experiment being performed, they may exhibit behavior similar to one or the other. They are, instead, *something else* entirely—something completely different from *anything* familiar to us in our macroscopic, everyday world. *Atoms*, Heisenberg once said, *are not “things”*.

The Copenhagen Interpretation also denies the objective, *independent* existence of certain *attributes* (such as position or momentum) of quantum ‘entities’ like photons, electrons, atoms, and molecules. Until actually *measured,* said Bohr, such attributes simply *do not exist*. And this implies the quantum ‘entity’ *itself* may not “objectively” exist—at least until some kind of measurement on it is performed.

Before an actual measurement is made of, say, an electron’s position, that electron—in a certain sense—can be said to be *everywhere*, or *nowhere* at all. In QM, the wave-function of an electron spreads throughout space…and, as per the “Born Rule”, the *probability* of finding the electron at a certain location depends on the *intensity* of the wave-function at that location. Since the wave-function’s intensity is *non*-vanishing throughout *all* of space, there’s a chance, however small, of finding the electron far from where we might expect it to be.

Consider, for instance, the single electron of a hydrogen atom. According to the Copenhagen Interpretation, if we look, we’ll *probably* find that electron somewhere in the vicinity of the atom’s nucleus, where the electron’s wave-function intensity is strongest. But there’s always a possibility (again, however small) we *migh*t find it somewhere across the lab, or across the world, or on the other side of our galaxy. For this reason, you’ll sometimes see statements in the popular media like “*an object can be in two places at once*”, or “*in the DSI experiment, a single photon passes through both slits*”. In *between* actual position measurements, all QM can tell us is the *probability*—via the “Born Rule”—of finding the electron (or photon, proton, atom, etc.) at some specific location.

The Copenhagen Interpretation insists that QM theory says all that *can* be said, so if a question—such as *what goes through the slits*?—cannot be directly answered by QM theory, the question itself must be regarded as *meaningless*.

(Here’s an example of another such meaningless question—one that *sounds* sensible enough, yet has no possible answer: “In a town where the barber shaves everyone who does not shave themselves, *who shaves the barber?*”

The English mathematician Bertrand Russell proposed this question to illustrate a serious paradox encountered in formal mathematical set theory: *Does the set of all sets contain itself*?)

In the Copenhagen Interpretation, the question “*what goes through the slits?*” is not at all paradoxical; it is, quite simply, *meaningless*. QM gives us the *probability* of getting a particular outcome for any given experiment, *but that is all it can do*. The reading of a meter on an instrument, the position of a flash on a screen, the click of a Geiger counter…all these are measurements in our macroscopic world, and QM tells us—with unprecedented accuracy—the *probability* of each. But to ask about the underlying *physical* ‘reality’ *before* the measurement is made is to ask a meaningless question, since formal QM theory has nothing whatsoever to say. In general, adherents to the Copenhagen Interpretation tend to agree with Wittgenstein’s famous quote, given above. And, regarding our central question—*what goes through the slits*?—the Copenhagen Interpretation tells us, in effect: *Don’t even bother to ask.*

It’s been said that the various interpretations of QM are really just a matter of taste. But the Copenhagen position is, itself, just such an *interpretation*—and one *not* to the taste of some pretty prominent physicists, such as Einstein, Schrödinger, de Broglie, Bohm and Bell.

CHAPTER 4

OBSERVER CREATED REALITY

> *If a tree falls in the woods, and no one is around, does it make a sound*?
>
> —Notorious philosophical question

In the earlier chapter on the DSI experiment, we said one conclusion that could be reached was that, *when we look for a wave, we find a wave, and when we look for a particle, we find a particle.*

Think about this for a moment, as it is an absolutely *extraordinary* statement. In some sense, *we* determine the nature of "*what goes through the slits*". Our choice of which experiment to perform seems to *create* the reality of our mysterious *something*.

Prof. John Wheeler (whom we've met before) proposed an extension of this idea—known as the "Delayed Choice Experiment"—with truly surprising implications. Imagine a *really* large version of the DSI experiment, one where the distance between the slits is appropriately scaled up, and the slit barrier to screen distance is, say, the distance from the Earth to the Sun. Here on Earth we set up two telescopes, with each telescope aimed at just one of the two slits.

As we run our hypothetical experiment, one photon at a time, and look through our telescopes, we see each single photon passing through *either* the left slit *or* the right. *Light,* we conclude*, seems to be made of particles*.

But now let's replace our two telescopes with a single, giant screen, and let the resultant pattern build up, photon by photon, over time. Just as in our “table-top” DSI experiment, we get an interference pattern. *Light,* we conclude, *seems to be made of waves.*

The speed of light is very fast, but not infinite. It takes light about 8 minutes to travel the distance between the Earth and the Sun—or, in our imaginary experiment, between the slit barrier and the screen. What if, during that 8 minute interval, *after the light has already passed through the slit barrier,* we change our minds, and swap out the telescopes for the giant screen, or vice-versa?

Not only does it appear as though *we* determine the *apparent* nature—particle or wave—of our mysterious *something,* but by delaying our choice as to *which* experiment to perform until *after* the light has already passed through the slit barrier, it seems we can actually do so *retroactively in time*. It’s as though our *current* choice of experiment can somehow change the *past* nature of our mysterious *something…before* it had passed through the slits.

Physicists have actually performed this experiment—on a much smaller scale, of course—and obtained the results just discussed.

“Quantum weirdness” like this doesn’t trouble supporters of the Copenhagen Interpretation at all—because, to their way of thinking, we’re talking about things that *cannot* be talked about.

In the Copenhagen Interpretation, QM is a way of determining the *probability* of macroscopic events…the pulse of a laser and the subsequent ‘flash’ on a screen, for example, or the radioactive decay of an atom and the subsequent ‘click’ of a Geiger counter. What happens *between* such events *cannot* be described, because QM theory simply has nothing to say.

As QM theory developed, there was a strong desire to place it on a rock-solid mathematical foundation. Yet another genius (we've met quite a few so far!)—John von Neumann—proceeded to do just that, casting QM in one of its most sophisticated mathematical forms, one that remains valid to this day.

In his monumental work, "*The Mathematical Foundations of Quantum Mechanics*", von Neumann realized there was a problem with the Copenhagen Interpretation, which, simply put, was this: measurement instruments (Geiger counters, phosphor screens, meters, and the like) are *themselves* composed of quantum 'entities' (such as atoms, molecules, etc.). Cutting off the quantum considerations *at* the measurement device (as per the Copenhagen Interpretation) seemed pretty arbitrary, and von Neumann wondered just where the line *should* be drawn, so to speak.

Being first and foremost a mathematician, von Neumann was a pretty hardheaded guy, yet he was forced—by his own reasoning—to conclude that there *is* no clear-cut point where the *quantum* probabilities become *ordinary* measurements. Von Neumann's work opened the door to speculations that *consciousness* itself was that limit. Perhaps it was consciousness that 'collapsed' the wave-function…? Just imagine von Neumann's surprise!

But what *level* of consciousness would be needed? A human's obviously would do, but what about that of an animal? Does Schrödinger's Cat collapse its *own* wave-function? Would a frog, fish, or insect have sufficient "consciousness" to do the trick? How about an amoeba, or a virus? A machine? *Where should we draw the line now*?

An obvious objection to the "Consciousness Created Reality" interpretation is that *all* of the observers must agree on the outcome of a quantum "event". If, for instance, one hundred honest physicists witness the “flash” of a single photon impacting a screen, *all* would agree on the position of that flash. If *conscious* observation is, in fact, the cause of the wave-function ‘collapse’, then one hundred *independently* conscious observers must have caused the *same* ‘collapse’…

Unless, of course, the consciousness of each of the one hundred observers is not really *independent* at all (as in one version of the “Consciousness Created Reality” interpretation). A still more radical possibility is that *you* are the only “real” consciousness in the room, and the other 99 observers are just figments of your imagination…and so is this book, and so am I.

Philosophers would call this last option *solipsism*, and here it appears in one of its most extravagant forms. *Consciousness*-created reality is a QM interpretation much favored by so-called “quantum mystics”, since it seems to validate the idea that physical reality is, in some sense, *created* by the mind.

As with so many examples of “quantum weirdness”, QM theory may *permit* such radical interpretations—but it does not necessarily *demand* them.

And, regarding our central question as to *what goes through the slits*?—the “Consciousness Created Reality” interpretation seems to answer: *Well, now…that’s up to you.*

CHAPTER 4

DECOHERENCE

> *Humpty Dumpty sat on a wall.*
> *Humpty Dumpty had a great fall.*
> *All the king's horses and all the king's men*
> *Couldn't put Humpty together again.*
>
> — Popular English nursery rhyme

We've seen how, in formal QM theory, an isolated quantum system (for example, a single photon *before* it encounters a detector, or a single electron *before* it registers on a phosphorescent screen) can be described by the QM wave-function.

One of the pre-eminent characteristics of the wave-function is its extreme *fragility*: any interaction with the "external world" will cause it to 'collapse'. The interaction may be *intentional*—observation with a macroscopic measuring device, like a photon detector, for example, or a phosphorescent screen. Or, the interaction could be *accidental*—collision with a random air molecule, say, or the impact of a stray cosmic ray. In either case, the original quantum system is no longer *isolated* from its environment, and the *superposition of states*, as described by the QM wave-function, 'collapses'.

First introduced by the German physicist H. Dieter Zeh in 1970, the idea of *decoherence* acknowledges the fact that an isolated quantum system (with its attendant "superposition of states") is *very* difficult to maintain. And the *larger* the quantum system is (think, perhaps, of Schrödinger's Cat, composed of billions upon billions of atoms), the greater the likelihood of some kind of unintentional interaction with the environment. For a large quantum system, the lifetime of the "pure" quantum superposition of states becomes *very* short, so the chances of observing a *macroscopic* system (again, like Schrödinger's Cat) in such a superposition of states becomes vanishingly small. Decoherence offers no explanation for the *mechanism* of the wave-function 'collapse', but it does account for the fact that we never *see* macroscopic systems in a superposition of states.

Decoherence also illustrates the relationship between QM theory and thermodynamics…in particular, the *Second Law of Thermodynamics*. The Second Law states (in *very* simplified terms): *disorder in a physical system always increases with time*. Short-lived exceptions to the Second Law can exist (living organisms, for example, gather and organize components of their environment into highly sophisticated, complex structures…like leaves and flowers, or hearts and brains). But, in the long run, the Second Law *always* prevails. That's why this section began with the quotation of a childish nursery rhyme—Humpty Dumpty's grim fate is shared by *all* physical systems, including quantum-level ones. (The Second Law of Thermodynamics has also been used to account for the so-called "Arrow of Time"…the general observation that, for macroscopic systems at least, time itself *appears* to proceed in one direction only: from the past to the future).

Interest in the ideas of decoherence was greatly renewed in the 1980's (and continues to this day), as physicists and computer scientists sought to exploit the possibilities of *quantum computing*.

Conventional computers are based on the idea of digital *bits* of information (each "bit" being represented by the binary "0" *or* "1" state so familiar to computer engineers and programmers). Quantum computing, on the other hand, is based on so-called *qbits—quantum* bits of information (a "0" *and* "1" *superposition* of states), as implemented by stable, isolated quantum systems.

A viable quantum computer would have vastly improved capabilities over more conventional digital computers. But *stable* quantum systems—and their associated "superposition of states"—are needed for a practical quantum computer…and these are extremely hard to preserve. *Any* contact with the external "environment" disturbs the system, and the "superposition of states" collapses.

Decoherence, then, can be regarded as more of a *principle* of quantum mechanics, rather than an *interpretation* of it. No explicit mechanism for the 'collapse' of the wave-function is offered by decoherence, but it does account for *why* macroscopic systems—like Schrödinger's Cat—aren't *observed* in the "superposition of states" so characteristic of QM. Some exceptions to this exist: "superconducting quantum interference devices", or SQUIDS, apparently show a *macroscopic* superposition of states. At extremely cold temperatures, electron currents can circulate in *opposite* directions—at the same time—through certain kinds of superconducting materials.

(For another possible *counter-example* to the principle of decoherence, see Appendix A: "The Quantum Eraser Experiment").

But, regarding our simple question as to *what goes through the slits*, decoherence answers, yet again, with the orthodox QM wave-function.

CHAPTER 4

"SPONTANEOUS COLLAPSE" MODELS OF QM

> *"We now focus on the following question: could there be a theory, predictively equivalent to quantum mechanics, but experimentally distinguishable from it?"*
>
> — G. Ghirardi and R. Romano, "*Is a Description Deeper Than the Quantum One Possible?"*

In the 'orthodox' theory of quantum mechanics, one of the main issues, so far as *interpretation* goes, is to account for how the many *possible* outcomes of an experiment—as described by the wave-function, with its accompanying "Born Rule" of probabilities—always result in just a *single* outcome being actually observed. The quantum "superposition of states" (Schrödinger's alive *and* dead cat, for example), at some point *disappears*, and we're left with just a single, definite state: an alive cat *or* a dead one. The decoherence principle explains why large, *macroscopic* objects (like cats) aren't usually seen in a superposition of states, but it cannot tell us why quantum-scale 'entities' (like photons, electrons, etc.) are never *directly* "observed" in a superposition of states.

To address this issue, a number of extensions and/or modifications of 'orthodox' QM theory have been proposed…and these are known as "Spontaneous Collapse" models. Currently, there exist several variations of these; in most, the 'orthodox' QM mathematics of the wave-function is *modified*, in one way or another, so that the wave-function *itself*—in a manner of speaking—"contains the seeds of its own destruction". And the various "Spontaneous Collapse" models *all* must meet certain necessary conditions:

1. Any modifications of the ‘orthodox’ QM wave-function mathematics must be *subtle,* so that the very successful predictive power of ‘orthodox’ QM theory for *microscopic* quantum systems (covering such phenomena as the energy levels and spectra of atoms, radioactive decay, etc.) is preserved. Any differences in the predictions arising from the modified mathematics should be so slight as to be barely discernible by experiment—if at *all*. “Spontaneous Collapse” models should also closely approximate the familiar “Born Rule” for the probabilities of experimental outcomes, just as in more ‘orthodox’ QM theory.

2. The changes should ensure that *macroscopic* systems (like Schrödinger’s Cat) obey the decoherence principle, and so are ordinarily never *observed* in a “superposition of states”.

3. The wave-function should collapse—*all by itself*—with no “measurement”, or outside “observer”, required.

An early form of “Spontaneous Collapse” theory was proposed by the Italian physicist G. Ghirardi and his colleagues, A. Rimini and T. Weber, in 1985.

Known as the “GRW” model, this theory fulfilled the three requirements listed above. The GRW modification of the ‘orthodox’ QM wave-function introduced two *new* parameters to QM: the first determined the average time it would take for a typical wave-function to ‘collapse’ (estimated, for a single quantum ‘entity’, to be on the order of 100 million years or so); the second parameter described the average spatial distance the wave-function would ‘collapse’ *into.*

This second parameter presents a somewhat surprising feature of the “GRW” model: it includes no point-like *particles* at all.

Instead, the “modified” wave-function collapses to a relatively small, but finite, region of space—approximately 10^{-5} centimeter (for perspective, that’s about 1/1,000th the diameter of a human hair).

In short, the “GRW” model predicts the wave-function representing, say, a single electron, will *randomly* and *spontaneously* ‘collapse’—all by itself—to a spatial region of *about* 10^{-5} centimeters, *about* once every 100 million years or so. As the number of quantum ‘entities’ comprising the quantum system increases, the more frequently the spontaneous collapse will occur, thus fulfilling the second condition listed above.

But, in the case of what we’d regard as an ordinary “measurement”, the wave-function still ‘collapses’ as soon as the measurement is made. In a typical, single-photon type DSI lab experiment, the wave-function associated with the photon will ‘collapse’ when it encounters the screen…and, ordinarily, that will take a *lot* less time than 100 million years.

Other “Spontaneous Collapse” type models have been proposed, using *different* kinds of modifications to the ‘orthodox’ QM mathematics…and the merits and drawbacks of these different models are still being actively debated. A sub-class of these kinds of models invokes *gravity* as the ‘trigger’ mechanism for the ‘spontaneous collapse’ of the QM wave-function.

Such “gravitationally induced” collapse models may be promising, but there still exist many outstanding issues …issues which researchers in this field believe will only be clarified—if not completely resolved—once a successful theory of *quantum gravity* has been developed. Many different approaches to quantum gravity are under current investigation (such as string theory, superstring theory, “M-theory”, “loop quantum gravity”, etc.)…and some of these approaches have been under active development for decades.

For the entire class of “Spontaneous Collapse” models (including the “gravitationally induced” collapse variations), advances in technology are now beginning to permit the design of actual experiments to *test* the different versions. Hopefully, these experiments will establish which—if any—of these models are truly viable, and help to distinguish which among them might best describe physical reality.

But, regarding our simple question as to *what goes through the slits*, all the “spontaneous collapse” models answer, once again: *a wave-function does*—but this time a wave-function whose mathematical description might differ, in subtle ways, from that found in more ‘orthodox’ QM theory.

THE TRANSACTIONAL INTERPRETATION

> *There once was a lady named Bright*
> *Whose speed was much faster than light*
> *She left one day, in a relative way*
> *And returned on the previous night*!
>
> —Popular limerick about Relativity

One of the great triumphs of 19th century “classical” physics was the development of the electromagnetic theory, by the Scottish physicist James Clerk Maxwell. In a true *tour de force* of mathematical wizardry, Maxwell not only unified two of the three fundamental forces known in his time—electricity and magnetism—he also predicted the existence of *electromagnetic waves*, laying the foundation for the future development of radio, television, radar, and all things wireless. As a bonus, Maxwell found that, in a vacuum, such waves would travel at a certain speed (approximately 300,000 kilometers per second, or 186,000 miles per second). From earlier experiments by others, this speed was already familiar to physicists—it was equal to the measured speed of light.

Just coincidence? Maxwell didn't think so…and he became the first to deduce that light *itself* must be an electromagnetic wave.

Maxwell's equations for his electromagnetic waves, like many other equations in physics, actually have *two* solutions: one positive, and one negative. Since no one knew what to do with the negative solutions, and they seemed to have no practical value, they were simply ignored.

(As an example, from your high-school algebra, you may recall that the square root of any positive number has *two* equally valid solutions. For instance, the square root of 64 can be either +8 *or* –8. Now suppose you want to enclose a small garden plot of 64 square feet. Good luck trying to do so with fence sides that are *negative* 8 feet long!)

Maxwell's equations for electromagnetic waves also have positive (called *retarded*) and negative (called *advanced*) solutions…with the retarded waves traveling *forward* in time, and the advanced waves traveling *backwards* in time.

In the 1980's, the American physicist John Cramer extended the use of these concepts to his "Transactional Interpretation" of QM. In the double-slit interference experiment, not only is a *retarded* wave-function emitted by the laser, but an *advanced* wave-function is emitted by the point on the screen where the photon *will* be detected. The advanced wave-function is emitted from the screen so that it reaches the laser source at *exactly* the same time the retarded wave is emitted *from* the source.

In other words, the advanced wave-function (the one originating at the *screen*) is emitted *before* the retarded wave-function is emitted by the laser. *The advanced wave-function travels* *backwards in time*. This "handshake" mechanism ensures the two wave-functions neatly cancel each other, so the 'collapse' of the wave-function problem is avoided: *the two wave-functions collapse one another*.

But regarding our question—*what goes through the slits*?—the Transactional Interpretation doesn't offer much help at all. Instead of addressing the physical meaning of a *single* wave-function, we've now got *two* wave-functions to worry about…and one of these travels *backwards* in time.

THE "MANY WORLDS" INTERPRETATIONS

> *When asked by the King of India how he'd like to be rewarded for inventing the wonderful new game of Chess, the Grand Vizier replied: "For each of the 64 squares on the board, grant me a grain of wheat for the first square, two grains for the second, four grains for the third, and so on, for all of the squares."*
>
> *"Is that all you wish?" asked the King, surprised by the modesty of the request. "Sire," said the Grand Vizier, "grant me this, and I shall own more wheat than there is in the world!"*
>
> —Ancient Indian legend regarding the origin of Chess

As mentioned earlier, two of the major issues in the interpretation of formal QM theory are the nature of the wave-function 'collapse', and the closely associated "Measurement Problem".

In the “Observer Created Reality” interpretation, the ‘collapse’ is caused by the observation—that is, the *measurement*—of the outcome of whatever experiment we’re performing. In the “Consciousness Created Reality” interpretations, the ‘collapse’ is caused by the *conscious* observation—human or otherwise—of the outcome of the experiment.

In his PhD thesis, Hugh Everett (one of John Wheeler’s students) took a uniquely different approach to the problem. *What if*, asked Everett, *there really exists only one wave-function, describing the entire Universe, including everything in it?* Such a “universal” or “global” wave-function would encompass *all* measuring instruments, *all* observers—*ourselves included*— and, of course, *all* of Schrödinger’s Cats. A “universal” wave-function implies that *everything* —again, *including ourselves*— exists in a superposition of states. A universal wave-function like this would *never* ‘collapse’, because—by definition—there is nothing *outside* of the Universe to cause its ‘collapse’. The existence of such a “universal” wave-function has some breathtaking consequences: it implies that *every possible outcome in every possible experiment occurs*…since the wave-function never ‘collapses’. Here we see Schrödinger’s “*catalog of outcomes*” writ large!

An obvious objection to this, of course, is that it’s not at all what we actually experience. We observe a photon, for example, as registering at one place on the screen, and *not* another. The Geiger counter clicks, or it doesn’t. When we open the container, Schrödinger’s Cat is either dead *or* alive. But, since *everything* is in a superposition of states, all these different outcomes exist…in what can best be described as different “worlds”, and the histories of each of these “worlds” are internally consistent.

Admittedly, at a single stroke, Everett’s theory neatly accounts for both the wave-function ‘collapse’ *and* the “Measurement Problem”. But, to reconcile this interpretation with our actual, real-world experience, Everett had to propose a *truly* bizarre notion: every time a quantum event occurs—here, there, across the room, or across the Galaxy—the *entire Universe* branches into multiple versions of itself, each of which contains a single "copy" of ourselves. Since each of these copies exists in just one of these "worlds", we observe only one of the possible outcomes. In one such "world", we find Schrödinger's Cat alive. But, in "the universe next door", copies of ourselves observe the cat as dead. Not only does Schrödinger's Cat exist in a quantum "superposition of states"—so does the Geiger counter…and so do *we*.

In Everett's "Many Worlds" interpretation, the entire Universe is constantly branching into slightly different versions of itself, again, and again, and again…and has been doing so since time began. Naturally, this interpretation is a favorite of science fiction writers, since it provides a basis for their stories of "parallel worlds" and "alternate histories".

If true, the philosophical implications of the "Many Worlds" interpretation are *staggering*; it's been estimated that there now must "exist" far more than 10^{100} (that's the number 1, followed by 100 zeros) independent "universes"…

The famous physicist John Bell once diplomatically described this multiplicity of "worlds" as "*extravagant*", and Prof. Wheeler (Everett's mentor) eventually abandoned this interpretation as having too much "*metaphysical baggage*". A later comment by Wheeler pronounced the "Many Worlds" interpretation as being "*cheap on assumptions, but costly in universes*."

Physicists have since developed several variations of Everett's original "Many Worlds" idea. In some versions, the "many worlds" can, on occasion, *recombine*, instead of forever branching independently of one another. This somewhat reduces the total number of "worlds", but calls for additional assumptions to account for when—and *how*—such recombination can take place.

In yet another version—the “Many Interacting Worlds” (MIW) interpretation—the different “worlds” can physically *influence* one another. These interactions can be described by mathematics which closely approximates the ‘orthodox’ QM theory’s wave-function…and the more “worlds” included, the better the approximation becomes. To achieve this, though, new assumptions—regarding the nature of these “inter-world” influences—need to be adopted. The mathematical arguments supporting the “MIW” interpretation are very sophisticated, and the number of different “worlds” required might be very, very large…perhaps, in fact, *infinitely* large.

Do the various “Many Worlds” interpretations help with our question as to *what goes through the slits*? Unfortunately, the answer is *not really*. These interpretations still retain, in one form or another, the wave-function, but now it has been elevated to a somewhat exalted, universe-duplicating status. The wave-function (or its “MIW” mathematical equivalent) still interferes with itself as it passes through the slits (much like a conventional wave)…but now it never ‘collapses’ at all.

CHAPTER 4

THE “SUM OVER HISTORIES” INTERPRETATION

> *"Would you like cream or lemon in your tea, Mr. Feynman?" It's Mrs. Eisenhart, pouring tea.*
>
> *"I'll have both, thank you," I say, still looking for where I'm going to sit, when suddenly I hear "Heh-heh-heh-heh-heh. Surely you're joking, Mr. Feynman."*
>
> —Prof. Richard Feynman, *Surely You’re Joking, Mr. Feynman*

Just for the sake of argument, suppose we insist upon regarding light, for example, as being composed of particle-like photons. Is there a way to reconcile this model with formal QM theory?

The American physicist Richard Feynman answered this question by proposing his “Sum Over Histories” interpretation. Like all of the QM interpretations we’ll look at, this one also comes with its own brand of “quantum weirdness”…

Feynman re-phrased the question as follows: *What path would a single photon follow on its way from the source to a point on the screen?*

You can never really know, answered Feynman, so you must consider *all* of them.

His interpretation showed that the idea of individual, particle-like photons could be retained—without conflicting with either QM theory or actual experiments—but only by stipulating that the probabilities of *all* possible paths available to the photon from the source to the point on the screen be taken into account. And there could be no exceptions to this rule: *every* conceivable path, no matter how “crazy”, had to be included.

Straight line paths, curved paths, zig-zag paths going backwards and forwards…the probability of *every* conceivable path had to be considered. The trick here was that the probabilities of all these “crazy” paths tended to cancel one another out, leaving just those few paths which made “sense”. But a consequence of this interpretation was that you could never say the photon had *one* definite history—by insisting the photon *migh*t have followed any one of *all* these possible paths, you had to acknowledge that a single photon had *many* possible histories, and each must be regarded as being as “real” as the next.

This “Sum Over Histories” approach was greatly expanded by Feynman; in fact, it is more of a new, different *formulation* of QM, known as the “Path Integral” model. Extensive applications of this model have been used in closely related subjects, such as particle physics, quantum field theory (“QFT”), and Quantum Electrodynamics (“QED”), the formalized theory of the interaction between light and matter. For his contributions to QED theory, Feynman shared a Nobel Prize.

But how does the “Sum Over Histories” model deal with our naïve question as to *what goes through the slits?* By answering: *a photon does, but one without a “unique” history…because it might have traveled any conceivable path to the screen.*

QUANTUM LOGIC

> *“Impossible? Why, I try to believe in at least six impossible things before breakfast every day!”*
>
> —Louis Caroll, *Alice in Wonderland*

As human beings, we’re used to thinking in terms of what’s known as *Boolean* logic: *If* some condition is met, *then* some event will occur. *If* this *or* that condition is met, then that *and* that event will follow…and so forth. George Boole, a 19th century professor in England, first formulated the mathematics of this very natural way of thinking about the world. By setting such everyday logic on firm mathematical ground, Boole’s work pioneered the way for later development of digital computers. Most computer hardware (*and* gates, *or* gates, etc.) and software (*If* this condition occurs, *then* take that action, etc.) is based on Boolean logic.

But what if the quantum world doesn’t work this way? What if our commonsense method of reasoning about the world simply doesn’t *apply* down at the quantum level? A lot of our discussion has had to do with the *attributes* of quantum objects, and these attributes come in two kinds: *static* and *dynamic*. Static attributes are fixed and unchanging—the charge of an electron, for instance, or its mass, or its intrinsic “spin” (we’ll be talking a lot more about spin in Chapter 10). Dynamic attributes are the ones that *can* change: position, momentum, energy, etc.

Starting with the work of von Neumann and Birkhoff, attempts have been made to develop new, non-Boolean forms of logic—*quantum* logics—to understand the counter-intuitive ways dynamic attributes can behave in quantum experiments.

An excellent demonstration of such non-intuitive logic can be found in what’s known as the “3-Polarizer Paradox”, and this is another experiment you can do an elementary version of at home.

All you’ll need are three of the lenses from cheap sunglasses, which you’re willing to sacrifice, and a cardboard tube into which they’ll fit snugly (I’ll leave the construction details to you; various plans can be found on the Internet).

The idea behind most sunglasses is pretty simple: the light we see in the everyday world—sunlight, for example—is *unpolarized* light (more about polarization in the next chapter).

Polarizing lenses—like the ones in sunglasses—sort light according to a *polarization axis*…think of a direction such as horizontal (H), vertical (V), or something diagonally (D) in between. Ideally, a sunglass lens permits only *one* direction of polarized light to pass through, and completely blocks the others. That's how sunglasses cut down on glare. The directions *horizontal*, *vertical*, etc. are just arbitrary labels, but the upshot is this: if you line up two separate sunglass lenses, then *rotate* the second lens 90 degrees to the first, all of the light is blocked. The first lens lets through only H-polarized light, say, but the second lens only lets through V-polarized light. The result? *No* light can pass all the way through both lenses. If the second lens is rotated at 0 degrees relative to the first, *all* the horizontally polarized light that passed through the first lens will also pass through the second.

So far, so good. Our standard, Boolean-logical way of thinking about the world still makes perfect sense.

But now comes the strange part. *Between* the H-polarized lens and the V-polarized lens, insert a third sunglass lens, *diagonally* rotated at 45 degrees to the other two. A remarkable thing happens: *some* of the light will now pass through all *three* polarizers. How can this be? If *no* light gets through when only H and V polarizers are used, how can adding a third polarizer—a D-polarizer—*between* the H and V polarizers allow some light to pass? This is *not* at all what we'd expect, using our commonsense, Boolean logic.

And yet, this is what happens.

Unfortunately, the various "Quantum Logic" interpretations don't really help much with our question—*what goes through the slits?*—except to tell us, perhaps: *Something does, but that something obeys non-Boolean logic, and will probably remain forever incomprehensible to human beings.*

CHAPTER 4

THE “INFORMATION” INTERPRETATION OF QM

> *“The quantization of nature is a consequence of the quantization of information. Moreover, reality and information are two sides of the same coin. It does not make sense to talk about reality without the notion of information about it, and it is pointless to talk about information without something where it refers to. What can be said about reality, defines what can exist.*”
>
> — J. Kofler and A. Zeilinger, “*The Information Interpretation of Quantum Mechanics and the Schrödinger’s Cat Paradox*”

The word “information”, in its common usage, is actually rather vague: we might refer to information regarding a person, a place, or a thing. Or, we might be referring to an event, a situation, a timetable, or a procedure. Sometimes we request, “More information, please,” on a subject…and sometimes we protest: “Too much information!”

In the fields of physics, mathematics, and engineering, however, the term “information” has a very precise meaning. *Any* kind of information can be represented or conveyed by a series of “yes/no” answers to a series of questions…somewhat like in the parlor game of “Twenty Questions”.

Modern digital computers illustrate the practical application of this idea. Not only text, but numbers, sounds and pictures—in short, *any* kind of information—can be represented, or *encoded*, as strings of binary digits—*bits*—consisting of ‘0’s’ and ‘1’s’. Each bit corresponds to an elementary “yes/no” answer.

Consider, for example, the complex scene of a beautiful sunset, captured by a digital camera. The entire scene is represented by millions of separate picture elements—*pixels*—arranged in a grid-like pattern. Each 'pixel' captures information about the brightness and color of its tiny portion of the scene, and both the brightness and color are encoded as binary numbers…that is, as digital '1's' and '0's'. The total number of '1's' and '0's' needed can be *enormous*. If each pixel can distinguish, for instance, 65,536 different colors, then 16 bits are required to encode this information (because the number 2, raised to the 16th power, equals 65,536). If each pixel can distinguish 1,024 different brightness levels, an additional 10 bits are needed (because 2^{10} = 1,024). Modern digital cameras typically have at least 8 "megapixels" of resolution. Each one of these 8 million pixels will generate 26 bits to encode just its single, miniscule portion of the scene. The *entire* scene, encoded in this fashion, requires 26 bits per pixel, multiplied by 8 million pixels…or 208 million bits. That's the equivalent of 208 million elementary "yes/no" questions…just to represent one still picture! Fortunately, modern semiconductor technology can handle all this information with ease.

The underlying idea, though, is this: *any* kind of "information"—no matter how simple, or how complex—can be broken down into a finite number of elementary "yes/no" questions.

As early as 1958, the German physicist/philosopher C. F. Weizsäcker proposed the use of what he referred to as "*ur-alternatives*"—the simplest, most elementary type of "yes/no" questions—as a way of describing the physical world (Weizsäcker further developed these ideas in his 1980 book, "*The Unity of Nature*"). Researchers in the field of quantum foundations applied this concept to QM theory itself, which also aims to describe nature at its most fundamental level.

In a digital computer, the basic “unit” of information is a single ‘bit’. In the “Information Interpretation” of QM, the most fundamental unit of information is regarded as the state of a single quantum system, and *a single, elementary quantum system can represent only one ‘bit’ of information.* (This assertion prompted Prof. John Wheeler to coin yet another clever phrase: “*the It from Bit*”).

Consider a single such quantum system—for example, a single electron. Every electron has an attribute called ‘spin’ (more on this in a later chapter), and, when *measured* along a given direction, the spin is found to be in *either* one of two possible states: ‘up’ or ‘down’. Once its spin state has been measured along a given direction, the electron has “given up” all the information available regarding its spin state…and any information about spin measurements along *other* directions is unavailable; only the *probabilities* of various outcomes can be given by QM. This accounts for the “quantum randomness” so inherent in QM theory. Of course, a future spin measurement of that same electron—along a *different* direction—will again yield a definite result (either spin ‘up’ or spin ‘down’), but this future result *cannot be predicted with certainty*…because the information to do so is simply not available.

Note how central the concept of *measurement* is to this interpretation of QM. “Information” about a quantum system can *only* be obtained by taking measurements. *No* “information” is available without an actual measurement taking place…so, in many ways, the “Information Interpretation” can be regarded as a *refinement* of the “Copenhagen Interpretation”, described earlier in this chapter. Without actual *measurements*, the “Information Interpretation” of QM becomes an explanation in search of a subject.

As discussed in a later chapter, though, “*measurement*” itself is a concept not as clearly defined as we might like to think…and it can also raise questions about the *observation* of the measurement: *Measurement by who*? *Measurement of what*? Put another way, can ‘information’ really exist all by itself, with no “observer” involved at all?

Let’s return, for a moment, to the example of the digital camera, and its captured scene of a sunset. Suppose a ‘glitch’ in the camera’s hardware causes the orderly sequence of ‘pixel’ data representing the scene —column by column, and row by row—to somehow become *scrambled*. No individual bit of “information” has gone missing, and each *individual* pixel’s string of binary data remains intact. Yet, when this scrambled information is displayed, the original scene is now *scrambled,* too—for an observer, at least, the *meaning* of the information has been lost…

There might be, it seems, *some* kind of subjective component to the concept of “information”…and perhaps one that shouldn’t be too quickly dismissed.

But our question—“*in the DSI experiment, what goes through the slits?*”—is really about what happens *between* actual measurements. So, within the measurement dependent framework of the “Information Interpretation”, the question itself must be regarded as *meaningless*, much as it was in the “Copenhagen Interpretation”.

And the answer, yet again, is: *Don’t even bother to ask.*

CHAPTER 4

HEISENBERG'S "DUPLEX" REALITY

> "*If wishes were horses, then beggars would ride*"
>
> —Traditional 16th Century English folk saying

In the interpretations we've looked at so far, the wave-function is regarded as a purely abstract construct—a mathematical mechanism, if you will—used to calculate the probabilities of outcomes in QM experiments.

Although a strong supporter of the Copenhagen Interpretation, Werner Heisenberg (of Uncertainty Principle fame) couldn't help but wonder about the *physical* nature of the wave-function, that mysterious *something* which seems to pass from the source to the screen in the DSI experiment.

Ordinary language might fail us badly in this discussion, warned Heisenberg, but he nevertheless attempted to describe that which is—perhaps—indescribable. Heisenberg's idea was that the world is composed of *two* kinds of reality—a "duplex reality".

One kind of reality is the ordinary world we're familiar with: flashes on a screen, or the position of a needle on a meter, or the click of a Geiger counter. But for the other type of reality, Heisenberg proposed taking the wave-function itself at face value: a physical reality composed of *potentia*, as he called them, toward the possible outcomes of an experiment.

Think, perhaps, of playing roulette in a casino. There comes a time *after* the dealer has called "No more bets," but *before* the winning number is known. The wheel is still spinning, and the ball jumps wildly about, between one possible outcome and another. This is *sort* of like the reality Heisenberg envisioned, except that, during this time, imagine you can not only *change* your bet (by altering the slit separation in the DSI experiment, for example)—you can even *move* your bet to a different table (by swapping the telescopes out for the screen, or vice-versa, like in the "Delayed Choice" experiment). Such a reality would be a turbulent, tumultuous thing—physically 'real', according to Heisenberg—yet with no more substance than a wish, or a dream.

When experimentally measured, this kind of nebulous 'reality' would be *actualized*—that is, turned into a single, concrete result: the observed position of a meter's needle, or the observed position of a flash on the screen.

Although far too vague to offer a definitive answer to our question—*what goes through the slits*?—Heisenberg at least acknowledged the question as a serious one, indeed.

THE DE BROGLIE-BOHM QUANTUM POTENTIAL FIELD INTERPRETATION

> "*Have we not a particle? Have we not a wave? Why not both*?"
>
> —J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics*

The American physicist David Bohm, having written what is still considered a standard textbook on QM, stayed for a while at Princeton University. During his stay, Bohm engaged in many thoughtful conversations with Einstein (who had settled just down the road, at the Institute for Advanced Study) about the nature of 'quantum reality'. Earlier in his career, Bohm had been a strong supporter of the Copenhagen Interpretation, but he eventually came to feel that something was *missing* from the Copenhagen point of view.

Bohm returned to an old idea of Louis de Broglie’s: the so-called “pilot-wave” hypothesis. De Broglie had run into difficulties developing his idea, but Bohm approached the problem a little differently, and found a new way to express the mathematics of QM.

Put simply, Bohm discovered he could represent the mathematics of QM in two parts. One part would represent an ordinary, conventional particle; the other part represented what Bohm termed the “quantum potential field”…an updated version of de Broglie’s original “pilot-wave”.

No more wondering about our question: *what goes through the slits*? The answer, said Bohm, was a good old-fashioned *particle*. And that particle would only go through one slit or the other, just as common sense demands.

In ‘conventional’ QM theory, as we’ve seen, the *objective* existence of attributes like a particle’s position or momentum are arguable (as is the very existence of the particle *itself*)…until an actual measurement is performed. By contrast, in the de Broglie-Bohm interpretation of QM, particles are treated as being objectively *real*—with *definite* positions, and *definite* trajectories—even *between* measurements. The Uncertainty Principle still applies, so we cannot know—*exactly*—both the particle’s initial position and momentum at the same time…and this prevents us from *knowing* each individual particle’s velocity and trajectory. But, in this interpretation, the particle definitely has them—even when it’s *not* being “observed”.

“*Finally!”* you might say—perhaps with a sense of relief. No more problems with the physical *meaning* of the wave-function, or its ‘collapse’; no more need for strange “quantum logics”, “Many Worlds”, or “Observer-Created” realities…

The price for Bohm’s vindication of “common sense”, though, was quite high. Each particle would be accompanied by its own unique “quantum potential field”, which would *steer* the particle along a given trajectory. But this field would not only have to pass through *both* slits instantaneously…it would have to blanket the entire *universe* instantaneously.

And the quantum potential field was uniquely *private*: it could *only* affect the particle it was associated with—so the field’s very *existence* could never be measured, or even verified, by any kind of outside interaction.

Also, unlike every other known field in physics, the *strength* of Bohm’s quantum potential field would never change with distance—it remains as strong on the far side of the universe as it is right next to its associated particle.

The de Broglie-Bohm interpretation was of a kind known as a ‘*hidden-variable*’ theory. Just as the name implies, hidden-variable type theories are (in simple terms) based on the assumption that there exist, in nature, attributes—*variables*—which can never be *directly* measured or observed. If these ‘hidden variables’ *could* be known, the ‘quantum randomness’ so inherent in ‘conventional’ QM theory could be replaced by definite, deterministic *predictions*. In the de Broglie-Bohm interpretation, the ‘hidden variable’ is the initial positions of the particles. (*Exact*, simultaneous knowledge of these positions, and their associated momenta, is prohibited, as discussed in Chapter 2, by Heisenberg’s Uncertainty Principle…and so they must remain forever *hidden*).

The de Broglie-Bohm Interpretation was a remarkable achievement, because at the time it was first proposed (in the early 1950’s), it was considered to be an *impossible* one.

John von Neumann, in his monumental volume, “*The Mathematical Foundations of Quantum Theory*”, had presented mathematical proofs *forbidding* the existence of *any* kind of ‘hidden-variable’ interpretations. Von Neumann had argued that *no* ‘hidden-variable’ theory—like de Broglie-Bohm’s—could ever reproduce *all* the predictions of the very successful ‘conventional’ quantum theory (for more on ‘hidden-variable theories’, see the next chapter). Yet Bohm’s interpretation did exactly that. So great was von Neumann’s stature as a mathematician, that his ‘proof’ remained unchallenged for over thirty years…and, because of this, the de Broglie-Bohm interpretation was, essentially, *ignored*.

By the mid-1960’s, though, von Neumann’s ‘proof’ was shown to be flawed, and there was a resurgence of interest in the de Broglie-Bohm interpretation. The *instantaneous* nature of the ‘quantum potential field’ still makes many physicists uneasy, since it seems to imply a violation of Einstein’s relativistic restriction that *no information can be conveyed faster than the speed of light*—but the de Broglie-Bohm interpretation could no longer be considered *impossible*.

A small—but very dedicated—group of physicists continue to research the viability and implications of what’s become known as “*Bohmian mechanics*” to this day, developing not only theoretical refinements to the original de Broglie-Bohm model, but also ways to experimentally *test* its predictions against those of ‘orthodox’ QM theory.

One of the original authors of the “GRW” spontaneous collapse model, Prof. Ghirardi, has shown that there may well be a large class of *alternative* interpretations *similar* to that of de Broglie-Bohm, and that these variations *also* agree with conventional QM predictions, while keeping the idea of objectively ‘real’, point-like particles.

So, regarding our question as to *what goes through the slits*?—the de Broglie-Bohm interpretation tells us, essentially, *two* things do: a very ordinary particle, and a very *extraordinary* quantum potential field.

THE “WHAT’S THE PROBLEM?” *NON*-INTERPRETATION OF QM

> “*There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature.*”
>
> — Prof. Niels Bohr

Let’s now consider what is, perhaps, both the first and last word in the debate over the *meaning* of the formal, mathematical QM theory: *no interpretation is needed at all.*

The apparent problem of “interpretation”, claim advocates of this view, lies *“not within our stars, but within ourselves”*…and struggling to find some *deeper* interpretation of QM is simply wrong-headed. Many (but not all) of the founders of QM thought that the theory had revealed an entirely new level of ‘reality’…a level so deep—and so *different*—that conventional human thought, concepts, and language are completely inadequate to describe it. According to supporters of the “What’s The Problem?” position, with sufficient exposure to QM theory, we’ll simply *get used to it*, and stop thinking there are *any* unresolved issues regarding its ‘interpretation’ at all.

But formal QM theory is, by its very nature, limited in its response to our question—*"In the DSI experiment, what goes through the slits?"*—to a listing of what our mysterious *something* is *not*:

It's *not* a 'conventional' wave—although it certainly exhibits wave-like behavior, *before* being detected at the screen.

It's not a 'conventional' particle, either—although whenever it's actually *measured,* it certainly *appears* to be one.

It cannot be some strange, new composite of wave *and* particle (a *wavicle…?*), since these are mutually exclusive concepts.

In Born's interpretation of formal QM theory, the wave-function is a *probability* wave, with no conceivable *physical* analog in our ordinary, macroscopic world…yet it remains demonstrably subject to the *physical* setup of whatever experiment we choose to perform.

By the process of elimination, formal QM theory seems to tell us that whatever the *something* is which goes from the source, through the slits, and on to the screen must be of a physical nature *completely* unfamiliar to us…indescribable in terms of any concept we know from our everyday experience. And the "What's the Problem?" *non*-interpretation tells us to just accept this as fact…and move on.

This kind of *non*-interpretation is somewhat reminiscent, though, of a classic example of circular logic:

What is heat? It's the absence of cold.
What is cold? Why, it's the absence of heat, of course!

Definitions like this are logically *consistent,* because they're self-contained, and can never really be argued with. But such "*definitions by elimination*"—for many people, anyway—leave something to be desired. And there's a certain sense of *finality* to them, as well: "*the case is closed; no need for further debate*."

"What's the Problem?" advocates might liken the current interpretational debates over QM theory to the confusion which ensued right after Einstein first proposed his theory of Special Relativity. It's true: physicists, philosophers, and laymen *were* disconcerted by the ideas—and the implications—of Einstein's new theory. Over time, though, people *did* get used to it…once the theory had been clearly understood.

In many ways, Einstein's Relativity was the last of the great *classical* theories. It involved space and time, mass and energy…concepts at least somewhat familiar to us all. What was so surprising about Einstein's theory was the *way* these concepts related to one another, becoming—under the right conditions—*interchangeable*. In Einstein's relativity, space could *become* time… mass could *become* energy…and so forth.

Quantum mechanics, though, is very, very different. In QM, even the fundamental *ideas* of position, momentum, energy and time are like nothing we're familiar with…and never will be again.

Although superficially similar to the Copenhagen Interpretation, the "What's the Problem?" *non*-interpretation is far more extreme. The Copenhagen Interpretation, at least, answers our question—"*What goes through the slits?"*—with a statement: "*Don't even bother to ask*."

The "What's the Problem?" *non*-interpretation instead replies to our question—somewhat dismissively—with a question of its own: "*Why would you bother to ask?*"

* * *

Here, then, is a brief summary of the interpretations we've looked at so far…with their answers to our central, naive question—"*in the DSI experiment, what goes through the slits*?"

The "Copenhagen Interpretation": *There is no micro-reality, so don't even ask*. QM gives us the probabilities of different outcomes by dealing with the *entire experimental system* (laser, slits and screen) as a kind of "black box". By definition, our question is *unanswerable*, since we're asking about the internal mechanisms of the "black box."

"Observer Created Reality": *Something* goes through the slits, but *we* determine its apparent nature—particle *or* wave—by *choosing* which experiment to perform…and our choice can affect the apparent nature of that *something* retroactively in time (as in the "Delayed Choice" experiment). Von Neumann's extension to this suggests it may be *consciousness* itself that causes the wave-function 'collapse'.

"Decoherence": the QM wave-function goes through the slits, and its extreme *fragility* explains why we never observe *macroscopic* quantum systems in the 'superposition of states' so characteristic of the wave-function. We never *see* Schrödinger's Cat as being both dead *and* alive.

"Spontaneous Collapse" Models: In these, the mathematics of the conventional QM wave-function is *modified*—in one way or another—to ensure the wave-function collapses *all by itself*…although, for a single quantum system, the time it takes for this self-collapse to occur may be on the order of millions of years. But any *measurement* of the wave-function *during* this time will cause an immediate, premature 'collapse'. In still other models, *gravity* may 'trigger' the self-collapse. In either case, for a typical laboratory DSI experiment, it's still a wave-function which goes through the slits…albeit one whose mathematics differ from that of 'orthodox' QM theory.

The “Transactional Interpretation”: A particle goes through the slits, but it’s guided by the “handshake” of *two* wave-functions… one of which travels *backwards* in time.

The “Many Worlds” Interpretations: Once again, it’s a wave-function going through the slits. In these interpretations, however, *the wave-function never collapses*; instead, the *entire universe* branches into multiple copies of itself, so as to accommodate *all* possible outcomes of an experiment. In the “Many Interacting Worlds” variation, the different “worlds” can physically *influence* one another, so, even in “one photon at a time” type DSI experiments, the buildup of the fringes is the result of interference between photons from different “worlds”.

The “Sum Over Histories” Interpretation: A photon goes through the slits, but one which *might* have followed any one of *every* conceivable path to the point on the screen where it is detected. Because of this, the photon cannot be regarded as having had one *definite* history; instead, that photon has many *possible* “histories”—all different, and all regarded as being equally “real”.

“Quantum Logic”: *Something* goes through the slits, but whatever that *something* may be, its attributes obey non-Boolean logic…and so it will probably remain forever *beyond* human comprehension.

The “Information Interpretation”: The idea of *measurement* plays a central role in this interpretation, because it is only through actual measurements that information can ever be obtained. But our question—“*what goes through the slits?*”—is concerned with what happens *between* measurements, so in this interpretation, much like in the Copenhagen Interpretation, our question must be regarded as *meaningless*.

Heisenberg's "Duplex Reality": Yet again, it's a wave-function which goes through the slits, but a wave-function with a weird kind of physical reality, made of *potentia*. Although Heisenberg considered these 'potentia' as having *some* kind of physical 'reality', their borderline existence is about as substantial as the outcome of a roulette game, *while the wheel is still spinning.*

The "de Broglie-Bohm Interpretation": *two* things go through the slits. The first is a conventional particle, which goes through just one slit *or* the other; the second is an accompanying 'quantum potential field', which goes through *both* slits…*instantaneously*. In fact, this field must instantaneously spread throughout the entire universe. And— unlike all other known fields—its strength remains absolutely *unchanged* with distance.

The "What's the Problem?" *Non*-Interpretation: QM theory—*just as is*—requires *no interpretation at all*. The mathematics of the theory has had unrivalled success in accounting for natural phenomena that were once *completely* beyond analysis by pre-quantum physical theories (*classical* physics). QM has also accurately *predicted* the results of every *new* experiment done to date, no matter how strange or counter-intuitive those results may seem. QM theory deals with nature at its most fundamental level, and nature—especially at this deep level—is under no obligation to "make sense" to human beings.

As to our question—"*what goes through the slits*?"—this *non*-interpretation has, really, nothing whatsoever to say.

* * *

The purpose of this chapter has been to introduce—or perhaps re-acquaint—readers with some of the current interpretations of quantum mechanics, especially with regards to the DSI experiment, and our simple question as to “*what goes through the slits*?”

Enigmatic wave-functions, and their equally enigmatic ‘collapse’; observation or *consciousness*-created realities; *backwards* time-travel; parallel universes and non-Boolean logics—these are some of the strange ideas put forth in the interpretations listed above. Remember, these interpretations are not the fringe beliefs of pseudo-scientists, or the creative imaginings of science fiction writers. Bizarre as they all may seem, these are *very* serious ideas, proposed by *very* serious researchers in the field.

So, which interpretation is right?

All of them? Or, perhaps, none of them?

Each interpretation—as it *must* be—is fully compatible not only with QM theory, but also with actual experimental results. In that sense, at least, they’re *all* correct. But how can such diverse approaches all be right? And most make at least some attempt to offer insight into our simple question: “*What goes through the slits*?”

It seems as though each different interpretation, while resolving *some* of the issues raised by QM, immediately gives rise to still others. And, while proponents of any particular interpretation can “live” with the issues raised by *their* particular viewpoint, advocates for a *different* interpretation *cannot*. In science, controversies like this are actually *healthy*, leading to debates… which, in turn, lead to progress.

Many of the interpretations just listed are related to the wave-function—that abstract, rather mysterious entity arising within the mathematics of QM theory itself. Other interpretations dispute the validity of our question, or even the need for it at all.

Some of the interpretations attempt to describe the *physical* nature of the wave-function; of these, still fewer talk explicitly about particles.

So, what *does* go through the slits? We seem to be faced with, really, only two choices.

Either accept that our mysterious *something* is of a physical nature beyond *anything* in our normal, everyday experience…or keep looking.

Like some twisting labyrinth deep underground, the Quantum Dragon’s lair has many ways to enter…but no certain way to leave.

CHAPTER 5

THE DRAGON’S CLAWS: “ENTANGLEMENT”, THE “EPR” EXPERIMENT, AND BELL’S INEQUALITY

> “*Entanglement is not one, but rather the characteristic of quantum mechanics.*”
>
> —Erwin Schrödinger

So far we’ve talked almost exclusively about the DSI experiment, and the various forms of “quantum weirdness” it entails. But there’s yet another experiment to consider, one that brings with it a new manifestation of “quantum weirdness”.

This chapter gets a little involved, because it talks about several inter-connected concepts in quantum physics—concepts that are more subtle, and more complex—than the ones we’ve dealt with so far. For that reason, this chapter is presented in two parts: the first introduces the QM concept of “entanglement”, discusses the famous EPR “thought” experiment, and concludes with an introduction to Prof. John Bell’s equally famous “Bell Inequality”. The second part ties all these ideas together, and discusses their implications for the nature of “quantum reality”.

Before beginning, though, a little history is in order…

Even though he’d helped to create the quantum theory, by the mid-1920’s, Einstein didn’t much care for the direction it was taking. QM itself was okay, so far as it went, but Einstein’s concern was with how QM dealt with the “dynamic” attributes of quantum ‘entities’. (In the last chapter we briefly discussed these—*static* attributes were things like mass, charge, and spin; *dynamic* attributes were things that could *change*, like position, momentum and polarization).

Einstein was convinced these dynamic attributes were objectively real, even *before* they were measured. Einstein adhered to what is called a *realist* point of view: although these attributes actually *existed*—independent from any observation—we wouldn't know their values until we actually measured them. QM, Einstein argued, must be *incomplete,* since it just plain failed to *fully* describe physical reality. Einstein believed in *classical* ignorance…as expressed in his famous quotation: "*I cannot believe God plays dice with the Universe*."

Bohr, on the other hand, disagreed. Quantum mechanics, argued Bohr, *was* complete, and the theory said all that *can* be said. *There is no micro-reality*, and it was the act of measurement itself that *created* the dynamic attributes…they simply didn't *exist* until a measurement actually took place. Bohr believed in *quantum* ignorance. (Bohr's not quite so well known reply to Einstein: "*Einstein, stop telling God what to do!*").

At the Solvay Conference in 1927, Einstein and Bohr engaged in what are now regarded as pivotal debates over the issue. Each morning, Einstein proposed a thought experiment, supporting his position. Then, each evening, Bohr produced a clever counter-argument, supporting *his* position (and often using Einstein's own arguments to do so). Overall, most of the physicists attending the conference thought Bohr came out on top.

But neither side could persuade the other, and, at that time, the technology didn't yet exist to settle the issue by experiment. Then, in conjunction with his Princeton colleagues Boris Podolsky and Nathan Rosen, Einstein launched a "surprise attack" on Bohr's position: the so-called "EPR Paper".

According to quantum mechanics, there are certain ways to generate two *identical* quantum 'entities'—pairs of photons, for example, or pairs of electrons—that fly apart in different directions. In formal QM theory, these pairs of quantum 'entities' are described by a common wave-function, and the two members of such a pair are said to be *entangled*.

Einstein and his colleagues proposed the following "thought" experiment, to challenge Bohr's views: suppose a source of entangled photons is located somewhere, say, in the mid-Atlantic ocean. One member of the entangled pair of photons is sent towards New York; the other is directed towards London.

Using basic conservation laws, reasoned the EPR team, a precise measurement of the photon's position in New York lets us *deduce* its entangled partner's position in London… *with no need for a second position measurement there*. And doesn't this mean, in turn, that the photon's position 'attribute' in London had an objectively *real* existence all along…independent of any actual measurement taking place?

The essence of the EPR argument was this: according to Bohr's view of QM, when a measurement is made on *one* member of an entangled pair, the common wave-function must 'collapse' for *both* members. A measurement made on one entangled partner can affect measurements made on the other*...no matter how far apart the two may be*.

This effect—called *non-locality*—means that a measurement made *here* (on Earth, for example) can affect a measurement performed *there* (in a distant galaxy, say)…and this *may* occur *faster than the speed of light.*

Einstein himself—in his Special Relativity theory—had proved *no* communication could be conveyed faster than the speed of light, yet that's exactly what Bohr's interpretation of QM seemed to call for. Many years later, Einstein famously referred to this as "*spooky action at a distance.*"

A stalemate had been reached, and neither side would concede defeat.

Then, in 1964, the Irish physicist John Bell developed a simple mathematical argument that could be used to *test* certain aspects of ‘quantum reality’. Bell’s argument didn’t come from QM theory, wave-functions, or even advanced mathematics; it was based on a simple algebraic inequality involving probabilities. “Bell’s Inequality” incorporated just two assumptions: *locality* and *objective realism*. “Locality” means that only influences within the immediate neighborhood—that is, influences travelling *less than or at the speed of light*—can affect the outcome of an experiment. “Objective realism” simply means the subjects of the experiment, and their properties, have an independent existence, whether they are observed—that is, *measured*—or not.

If a quantum experiment *agreed* with Bell’s Inequality, then ‘quantum reality’ could be both *local* and *objectively real*. If, however, the quantum experiment *violated* Bell’s Inequality, ‘quantum reality’ must be either *non-local, not objectively real*...or, perhaps, *both*.

There are all kinds of imaginative, colorful explanations of Bell’s Inequality available. You can read several different versions in the books listed in the bibliography (descriptions using tennis balls, coins, playing cards, etc.). Bell’s Inequality is *so* important to any discussion of ‘quantum reality’ that it’s worthwhile to take a detour here, and first describe Bell’s Inequality as it applies to *everyday objects* in our everyday world…and the objects we’ll use are jellybeans.

Imagine a large jar containing, say, 3,000 red and green jellybeans. There are an equal number of red and green jellybeans, and the jar has been thoroughly mixed. Now, if you don’t look, you’ve got an equal chance of randomly picking either a red or a green jellybean from the jar.

Next—and still without looking—randomly pick out three jellybeans. Let’s call this first group of three jellybeans Set 1. *Now* you can look at Set 1, and carefully write down the color of each jellybean *in the order in which you picked them* (for example, Red, Red, and Green).

Again, *without looking*, pick a second set of three jellybeans, *then* look at them, and record their colors in the order in which they were picked. We’ll call this second group of three jellybeans Set 2.

Repeat this process 998 more times, keeping each set of three randomly chosen jellybeans separate, so your last set of three randomly selected jellybeans is Set 1000. Abbreviating R for Red and G for Green, there are only 8 possible color combinations for each set of three jellybeans: RRR, RRG, RGR, GRR, GGR, GRG, RGG, and GGG. After doing this a thousand times, and keeping track of each result, you’ll have a list of 1000 separate entries, looking something like this:

Set 1: RGG
Set 2: GRG
Set 3: GGR…
…
Set 1000: RGR

Remember, this is an example only; since each set is chosen at *random*, you’ll most likely get a *completely* different list of results.

Since there are eight possible combinations of colors for each *set* of three jellybeans, and you’re picking the jellybeans at random from the jar, the *probability* of picking a *particular* set of three colors (say, for example, RGG) is 1/8. That means your list should have *about* 1000/8 or *about* 125 sets of RGG jellybeans. Of course, when you actually *do* this experiment, you might get *fewer* sets of, say, RGG jellybeans, or you might get *more* sets of RGG jellybeans. But, if you repeat the experiment again and again, your results will approximate about 125 sets of RGG jellybeans. It’s just like flipping a ‘fair’ coin a thousand times…you *might* get, say, 600 heads, or 600 tails, but—on average—you’ll get about 500 heads, and 500 tails.

You should also get *about* 125 sets of RRR jellybeans, 125 sets of GGG jellybeans, 125 sets of GRG, jellybeans, and so on. All this is just basic probability…

Now, suppose we’re only interested in the colors picked in the first and second positions of each set of three jellybeans. For example, out of our thousand sets of jellybeans, how many sets have green in the first position and red in the second position? Or, for another example, how many sets out of the thousand have a green in the second position, and a red in the third position? How do we handle questions like these?

Let’s use another abbreviation—“X”—for the colors in the positions we *don’t* care about. Now we can re-phrase the above two questions like this: how many sets are GRX? How many sets are XGR?

So, how many sets out of our list of 1000 *will* be GRX? In other words, how many sets will have a green jellybean in the first position, and a red in the second? For this example, we just *don’t care* what color is in the third position. Well, we’ll need to do some addition here. There will be *about* 125 GR*G* sets, and *about* 125 GR*R* sets; adding these numbers tells us there should be *about* 250 GRX sets. Makes sense, doesn’t it?

For a random list of 1000 sets, probability tells us the number of GRX sets must be *greater than or equal to* the number of GRG sets. And the number of GRX sets can also *only* be greater than or equal to the number of GRR sets. Likewise, the number of XRG sets must be *greater than or equal to* the number of RRG sets, and greater than or equal to the number of GRG sets.

With these ideas in mind, we're ready to tackle Bell's Inequality— as applied to jellybeans...

First, count up all the sets containing *only* red jellybeans, and call this number #RRR. Next, count up the number of sets containing *only* green jellybeans, and call this number #GGG. Let's continue by counting up the number of sets for the different possible color combinations, #RRG…#RGR…#GRR…etc.

When we're done, we'll have actual values for the *number* of jellybean sets containing the different possible color combinations: #RRR, #GGG, #RRG, #RGR… and so on.

Since we've got a total of 1000 *sets* of jellybeans (with three jellybeans in each set), the sum of all these numbers (#RRR, #GGG, #RRG…etc.) must add up to 1000.

Now, using our shorthand notation, we can obtain Bell's Inequality by the following argument:

Step 1: $\#RGX = \#RGG + \#RGR$, so $\#RGX \geq \#RGG$

Step 2: $\#XRG = \#RRG + \#GRG$, so $\#XRG \geq \#RRG$

Combining steps 1 and 2:

Step 3: $\#RGX + \#XRG \geq \#RGG + \#RRG$

Since $\#RGG + \#RRG = \#RXG$, we get:

Step 4: $\#RGX + \#XRG \geq \#RXG$

Step 4 is Bell's Inequality. If you actually *do* this experiment with jellybeans, no matter what your particular results turn out to be, your answers will *always* obey Bell's Inequality…*every time.*

You can imagine replacing the jellybeans with other ordinary objects (coins, for example), and the two-valued attribute of color—red *or* green—with the two-valued attribute of heads *o*r tails…and you'll still find your results *always* obey Bell's Inequality…

The question is, if we use *quantum* 'entities' (photons or electrons, for example) and *quantum* attributes (polarization or spin direction, for example), will the results also agree with Bell's Inequality?

While you're pondering this question, go ahead and have a few jellybeans. You've earned them!

By this point, though, you're probably wondering, *"So what does all this have to do with the Einstein-Bohr debates, the EPR paper…and the nature of 'quantum reality'…?"* In the continuation of this chapter, we'll consider an example of a 'realist' model of photon polarization, and see how such a model holds up when *tested* against Bell's Inequality.

CHAPTER 5 (Continued…)

THE DRAGON’S CLAWS: HIDDEN-VARIABLE MODELS, NON-LOCALITY, AND BELL TESTS OF ‘QUANTUM REALITY’

> *“…the formalism leading to Bell's inequalities is very general and reasonable. What is surprising is that such a reasonable formalism conflicts with quantum mechanics.”*
>
> — Prof. Alain Aspect, *"Bell's Theorem: The Naïve View of an Experimentalist"*, in Quantum [Un]speakables (2002)

> *“What Bell’s theorem, together with the experimental results, proves to be impossible (subject to a few caveats we will attend to) is not determinism or hidden variables or realism but locality, in a perfectly clear sense. What Bell proved, and what theoretical physics has not yet properly absorbed, is that the physical world itself is non-local.”*
>
> — Prof. Tim Maudlin, *"What Bell Did"*, Journal of Physics A: Mathematical and Theoretical (2014)

In the first part of this chapter, we saw how, in the original EPR paper, a “thought” experiment was proposed—one using entangled photon *positions* to illustrate Einstein’s view regarding the “incompleteness” of quantum mechanics. In practice, though, such an experiment would be *very* difficult to perform. Prof. David Bohm (of “de Broglie-Bohm” interpretation fame), suggested a substitute for the EPR "thought" experiment, one which might actually be carried out. Bohm's more practical version replaced the measurements of entangled photon *positions* with measurements of entangled photon *polarizations*.

In Chapter 4 we talked briefly about photon polarization…but now we're going to need a little more detail…

Photon polarization is *experimentally* measured by the use of optical elements called *polarizers*. It should be mentioned here that there are actually several different *kinds* of polarizers available. One type is like that found in Polaroid™ sunglass lenses: a photon will either *pass* through it, or be completely blocked by it. A different type of polarizer *passes* every photon, but each photon "emerges" from this kind of polarizer in one of two possible "channels", arbitrarily labelled as the "horizontal" and "vertical" channels. For simplicity, in the remainder of this book, we'll always be referring to the first kind of polarizer.

When we say ordinary light (sunlight, incandescent lighting, etc.) is unpolarized, what we *really* mean is that the photons making up such light are *randomly* polarized.

As we saw earlier, when aimed at a single polarizer set at *any* chosen angle, about half of the *randomly* polarized photons will pass through it; the other half will not. If our polarizer is set at, say, 0 degrees (remember, this is just an arbitrary direction), we can say any photons which *do* pass through it are *now* polarized at 0 degrees…and *all* of these photons, in turn, will pass through any subsequent polarizers also set at 0 degrees.

If we *rotate* our single polarizer by 90 degrees, again only about half the randomly polarized photons will pass through it. This time, we can regard *these* photons as being polarized at 90 degrees, and *all* of these 90 degree polarized photons will pass through any additional polarizers set at 90 degrees.

As you'll recall from the "3-Polarizer Paradox" (discussed in Chapter 4), *no* "0 degree" polarized photons will pass through a polarizer set at 90 degrees…and vice-versa.

But what if the second polarizer is rotated at an angle somewhere *between* 0 and 90 degrees, relative to the first? Will a photon which *has* passed through a polarizer set at, say, 0 degrees *also* pass through a subsequent polarizer rotated at, say, 22.5 degrees? 45 degrees? 60 degrees?

The answer is *maybe*. This probability is given by a simple rule in QM…and here it is:

$$P = (\cos^2 \theta)$$

where P is the *probability* a photon which *has* passed through a polarizer set at 0 degrees will then pass through a second polarizer, rotated at θ degrees relative to the first.

(Actually, a form of this rule was first discovered by the French physicist Etienne-Louis Malus, back in the 18th century…long before quantum mechanics was even *dreamt* of. While investigating the optical properties of certain mineral crystals, Malus found that ordinary light passing through a single such crystal was reduced to about one half its original brightness. When this light was then passed through a *second* crystal, the brightness of the light emerging depended on the *rotation* angle of the second crystal, relative to the first. In effect, Malus had discovered the principle of polarization. His rule, known as the "Malus Law" is given by:

$$I = I_o \ \tfrac{1}{2} (\cos^2 \theta)$$

where I is the light's intensity after *emerging* from the second crystal, I_o is the incident light's *original* intensity *before* passing through the first crystal, and θ is the rotation angle *between* the two crystals. Of course, in his time, Malus knew nothing of photons. But he *could* crudely measure the intensity—that is the *brightness*—of beams of light).

From basic trigonometry, we can also express the probability, $\overline{P}$, a photon which *has* passed a first polarizer set at 0 degrees *won't* pass a subsequent polarizer rotated at θ degrees:

$\overline{P} = (1-\cos^2 \theta)$ or, equivalently: $\overline{P} = (\sin^2 \theta)$

Now, according to Einstein's "realist" point of view, every photon has an *objectively* existing polarization state, *whether it is measured or not*. Any photon will pass a polarizer if the two have the same polarization angle. In the "realist" view, a photon which *passes* through a polarizer at 0 degrees can be said to have *been* polarized at 0 degrees…*even before it encountered the polarizer*. (As mentioned earlier, Bohr *completely* disagreed with this idea). From a "realist" standpoint, a photon that passes a polarizer at, say, 22.5 degrees must have already *been* polarized at 22.5 degrees…and so forth.

In the "realist" view, it's as if, at its moment of creation, each photon has a kind of "instruction label" attached to it, telling it what to do (that is, pass *or* fail) at any and every polarizer angle it might encounter. This is an *example* of a so-called "hidden-variable" model of photon polarization.

We can imagine the photon's "instruction label" as being composed of "1's" and "0's", sort of like the barcode found on products in supermarkets, hardware stores, etc.

In this example of a *realist* "hidden-variable" model, each position in the photon's "barcode" tells the photon how to behave if it encounters a polarizer set to any specific angle. Just as an example, the very first position in the photon's barcode might tell the photon what to do if it encounters a polarizer set at, say, 0 degrees. If there’s a “1” in this first “barcode” position, the photon will pass through the polarizer; if there’s a “0” in this first position, the photon will fail to pass through the polarizer. Likewise, the second position in the photon’s “barcode” could determine whether the photon passes or fails at a polarizer set to, say, 1 degree…and so forth.

In the following discussion, we’re going to look at the implications—and consequences—of this *realist* view of a *hidden-variable model* of photon polarization.

In the *realist* model, our photon’s hidden-variable “barcode” should have an *infinite* number of positions, since the photon may encounter a polarizer set to an infinite number of possible rotation angles between 0 and 90 degrees.

Fortunately, though, we aren’t going to need to consider this many “barcode” positions. We’re only going to be concerned with *three* possible polarizer angles: 0 degrees, 22.5 degrees, and 45 degrees (the reason for choosing these three particular angles will shortly become apparent). Our photon’s *hidden-variable* “barcode” can now be truncated to only 3 positions, corresponding to 0, 22.5, and 45 degrees, since we simply don’t *care* what the photon will do at other polarizer angles. Each of the three “barcode” positions will contain either a “0” or a “1”.

Just to be clear, let’s consider some examples. If our photon’s *hidden-variable* “barcode” is 0,0,1 the photon would *fail* to pass through a polarizer set at 0 degrees, *fail* to pass a polarizer set at 22.5 degrees, but *pass* through a polarizer set at 45 degrees. If the photon’s “barcode” happens to be 1,0,1, it would *pass* through a polarizer set at 0 degrees, *fail* to pass a polarizer set at 22.5 degrees, and *pass* a polarizer set at 45 degrees…and so on.

Recall that, for a *randomly* polarized photon—that is, for a photon whose polarization has *not yet been measured at all*—the chance it will pass through a polarizer set at *any* specific angle is about one half. For *each* of the three positions on a *randomly* polarized photon's "barcode", this means the chances of getting a "0" or a "1" are equally likely. *Before* its polarization is actually *measured*, that means the *entire* "barcode" for a randomly polarized photon must also be *random*…a randomly polarized photon with a 111 "barcode" is just as likely as a randomly polarized photon with a 000 "barcode", or a 010 "barcode"… etc. The "barcode" is just like a "Pick Three" lottery ticket, but the only digits that can *ever* come up are 0 or 1.

And now we see the reason for the rather lengthy explanation of Bell's Inequality—using jellybeans—in the first part of this chapter.

In the *example* of a realist, hidden-variable model of photon polarization we're considering here, each randomly polarized photon is analogous to a *single* set of three randomly chosen jellybeans. But now we've replaced the two-valued attribute of jellybean *color*—red *or* green—with the two-valued attribute of the photon passing *or* failing at any one of our three chosen polarizer angles (0 degrees, 22.5 degrees, and 45 degrees).

So, what's the probability of a *randomly* polarized photon having a *specific* "barcode"? Since there are only 8 possibilities (0,0,0…0,0,1…0,1,0…0,1,1…1,0,0…1,0,1…1,1,0…1,1,1), the chances are 1/8. We can manipulate combinations of these "barcodes" to get other, useful probabilities as well…

For convenience, let's introduce a shorthand notation. P{0,0,1}, for example, represents the *probability* a randomly polarized photon has a "barcode" of 0,0,1…so P{0,0,1} is the probability a randomly polarized photon would *fail* to pass a polarizer set at either 0 degrees or 22.5 degrees, but would *pass* a polarizer set at 45 degrees; P{1,1,0} is the probability a random photon would *pass* through a polarizer set at 0 degrees or 22.5 degrees, but would *fail* to pass a polarizer set at 45 degrees…and so on. If we don’t *care* what the photon would do at one of our three polarizer angles, we can just fill in the associated barcode position with an “X”.

For illustration, suppose we’re interested in the probability a randomly polarized photon would *pass* a polarizer set at either 0 or 22.5 degrees, but we *don’t care* what it would do at a polarizer set for 45 degrees. Using our notation, we can write: P{1,1,X} = P{1,1,0} + P{1,1,1}. In plain English, this just says “the probability a randomly polarized photon would pass a polarizer set at either 0 degrees or 22.5 degrees is the *sum* of the probability the photon would *pass* at 0 and 22.5 degrees, but *fail* at 45 degrees, *plus* the probability the photon would pass at 0, 22.5 and 45 degrees”.

Here’s another example: what’s the probability a randomly polarized photon would pass a polarizer set for 45 degrees? We can write this as P{X,X,1} = P{0,0,1} + P{0,1,1} + P{1,0,1} + P{1,1,1}. I’ll leave the cumbersome English translation to you.

Now that we’ve got a convenient, shorthand notation for describing a randomly polarized photon’s probability of passing (or failing) at any of our three polarizer angles, we can derive Bell’s Inequality for photon polarizations…and we can proceed just as we did in the earlier, “jellybean” example.

The awkward English translations for the first and last steps are written out below them—so you can see why our shorthand notation comes in so handy. The derivation of Bell’s Inequality is really pretty simple, and goes like this:

1. P{1,0,X} = P{1,0,0} + P{1,0,1}; so P{1,0,X} ≥ P{1,0,0}

(The probability a random photon would pass a polarizer at 0 degrees, but fail one at 22.5 degrees is greater than or equal to the probability the photon would pass at 0 degrees, but fail at 22.5 *and* 45 degrees).

2. P{X,1,0} = P{1,1,0} + P{0,1,0}; so P{X,1,0} $\geq$ P{1,1,0}

Combining steps 1 and 2:

3. P{1,0,X} + P{X,1,0} $\geq$ P{1,0,0} + P{1,1,0}

Since P{1,0,0} + P{1,1,0} = P{1,X,0}, we get:

4. P{1,0,X} + P{X,1,0} $\geq$ P{1,X,0}

(The probability a random photon would pass a polarizer at 0 degrees, but fail one at 22.5 degrees *plus* the probability a random photon would pass a polarizer at 22.5 degrees, but fail one at 45 degrees is equal to or greater than the probability a random photon would pass a polarizer at 0 degrees, but fail one at 45 degrees).

That's it; that last step—step 4—is Bell's Inequality…applied to our example 'realist' model of photon polarization. It's worthwhile to be sure you really do "get it", because—although it's quite simple—it's also *very* important. Ordinary, everyday objects (like coins, playing cards…or jellybeans) will *always* obey Bell's Inequality, as detailed in the first part of this chapter.

The question is, do *quantum* 'entities' (like photons, electrons, etc.)?

If quantum 'entities' do obey this simple inequality, then Einstein was *right*: the dynamic attribute of a photon's polarization is *objectively real*, even *before* it's measured. And 'quantum reality' can also be *local*, as our "common sense"—and Special Relativity—would have it.

But, if quantum ‘entities’ *violate* Bell’s simple inequality, then Einstein (in this instance, at least) must be *mistaken*—either the dynamic attribute of a photon’s polarization doesn’t *objectively exist* until it is actually measured, *or* there really is such a thing as “*spooky action at a distance*.” If Bell’s Inequality *isn’t* obeyed by quantum ‘entities’, the ‘realist’ version of ‘quantum reality’ (as in our example ‘hidden-variable’ model of photon polarization) cannot be true, and ‘*quantum reality’ must be either non-local, non-objective…or both.*

Bell’s Inequality leaves us no “wriggle room” at all here—there are no loopholes, no third alternatives, and no way to dispute the results.

With Bell’s Inequality in hand, it finally became possible to experimentally *test* the nature of ‘quantum reality’…

Using a source of single, randomly polarized photons won’t do, since we only get to measure an individual photon’s polarization *once*, by sending it at a single polarizer, and seeing if it *passes* or *fails* to pass through. In other words, if we send a single, random photon at a polarizer set for 0 degrees, and it passes, *in the ‘realist’ view* we can say that photon *was* polarized at 0 degrees (in the example used above, its first “barcode” position contained a “1”). Also, we know from experiment that this same photon, *after* passing through the 0 degree polarizer, will *definitely* pass through any subsequent polarizers also set at 0 degrees. But how can we be sure the first polarizer didn’t *change* other positions in the photon’s *original* “barcode” from their original values (“0” or “1”)?

Checking a randomly polarized photon’s polarization *after* it has already passed through a polarizer isn’t really a fair test…it’s possible the polarizer may have *altered* the photon’s original hidden-variable “barcode”.

But Bell's Inequality calls for measurement of the values in *two* of the three positions in the photon's original "barcode": at the first and second positions (corresponding to polarizer settings of 0 and 22.5 degrees), at the second and third positions (22.5 and 45 degrees), and at the first and third positions (0 and 45 degrees).

How can this be done?

By using pairs of *entangled*, randomly polarized photons, which fly apart in different directions. (In our earlier "jellybean" example, this is like having a lab partner who—from their own jar of jellybeans—*duplicates* each one of your randomly chosen sets of three jellybeans. Now each of *your* 1000 sets of jellybeans will be identical to your partner's, and each one of your sets of three jellybeans will have the same colors, in the same order, as *theirs*. Each two *identical* sets of jellybeans—yours and your partner's—are, in effect, *entangled*).

Now we can send one of the photons towards a polarizer at one side of the experiment, while its entangled partner travels towards a polarizer on the other side of the experiment. Since they're entangled, the two photons should be *identical,* and so, from the "realist" standpoint, should have identical hidden-variable "barcodes". In effect, we now get to measure the original, randomly polarized photon's polarization (its "barcode") *twice*…and, if we like, at two *different* polarizer settings. (Using our "jellybean" analogy, *you* might determine the *first* color in *your* Set 1 of three jellybeans is Green…but your lab partner might look at the *second* color in *their* duplicate Set 1, and determine it is Red).

Creating—and measuring—entangled photon pairs is a tricky business. Several actual experimental tests of Bell's Inequality have been done; the one we'll discuss here was performed by Prof. Alain Aspect at the University of Paris. Aspect's experiment generated entangled pairs of *randomly* polarized photons, which then travelled in different directions; the polarizations of the *separated* members of each entangled photon pair were then measured at the two sides of his experiment.

Since a randomly polarized photon has about a 50% chance of passing (or failing) at *any* polarizer angle, either side of Aspect's experiment should just register a *random* sequence of photons passing or failing the polarizer on that side.

But, when the random sequences from the two sides of the experiment were *compared,* entangled photon pair by entangled photon pair, Aspect could *reconstruct* the values in *two* of the three "barcode" positions. In effect, he could measure the probability a randomly polarized photon would, say, pass at some polarizer angle, but its entangled, *identically polarized* partner would fail at a different polarizer angle.

When the polarizers at both sides of the experiment were set to the *same* angle, we'd expect to see a *perfect* correlation in the random sequences detected—because entangled photons, with identical "barcodes", should behave the same way at identical polarizer settings.

Below are listed *example* random sequences of results at Side A and Side B of the experiment, *when the polarizers at both sides of the experiment are set to the same angle*. If a photon passes its respective polarizer, the result is recorded as a "1"; if it fails, the result is recorded as a "0". When the two sides of the experiment yield the *same* result, this *correlation* is recorded as a "1"; if they're *different*, this *anti*-correlation is also recorded as a "1":

SIDE A: 100111010011110000
SIDE B: 100111010011110000

CORRELATION: 111111111111111111

Not surprisingly, that's what Aspect's experiment found.

Next, if the polarizer at Side A of the experiment is set at 0 degrees, but the polarizer at Side B is set at 90 degrees, we'd expect the sequences to be the exact *opposites* of each other (so, if a photon *passes* at one side, its entangled partner would *fail* at the other side…and vice-versa):

SIDE A: 100111010011110000
SIDE B: 011000101100001111

ANTI-CORRELATION: 111111111111111111

And that's also what the experiment confirmed.

But what if the *difference* in the polarizer rotation angles is somewhere *between* 0 degrees and 90 degrees?

Earlier, we saw the simple rule QM has for this situation. This same rule should predict the probability of *correlations* between the random sequences of photons passing or failing at each side of the experiment.

First, Aspect checked the QM prediction for the first term in Bell's Inequality—the probability a randomly polarized photon would *pass* through a polarizer set at 0 degrees, but its entangled partner would *fail* at a polarizer set to 22.5 degrees (in other words, the probability of a randomly polarized photon having a "barcode" of 1,0,X). In our shorthand notation, Aspect measured P{1,0,X}…the first term in Bell's Inequality.

To do this, the polarizer on side A of the experiment was set to 0 degrees, and the polarizer on side B was set to 22.5 degrees. Then the random sequences from both sides were compared, entangled photon pair-by-pair, to get the correlation. Since the difference in the polarizer rotation angles is 22.5 degrees, the QM rule (as listed on page 90) should be:

$P\{1,0,X\} = \frac{1}{2} \sin^2 \theta$ or, $P\{1,0,X\} = \frac{1}{2} \sin^2 (22.5°)$

The results agreed perfectly with the QM prediction.

Next, Aspect checked the second term of Bell's Inequality…the probability randomly polarized photons would *pass* a polarizer set at 22.5 degrees, but would *fail* at a polarizer set at 45 degrees (in our shorthand notation, P{X,1,0}). The *difference* in the polarizer rotation angles is again 22.5 degrees, and the QM rule is:

$P\{X,1,0\} = \frac{1}{2} \sin^2 (22.5°)$

These results also agreed with the QM prediction.

Finally, the last term of Bell's Inequality was checked…the probability randomly polarized photons would pass a polarizer set at 0 degrees, but fail at a polarizer set at 45 degrees…in our shorthand notation, P{1,X,0}. For this test, the *difference* in the polarizer rotation angles is 45 degrees, so the QM rule is now:

$P\{1,X,0\} = \frac{1}{2} \sin^2 (45°)$

Again, there was perfect agreement with the QM prediction.

So, according to Bell's Inequality (step 4, from page 94):

$\frac{1}{2} \sin^2 (22.5°) + \frac{1}{2} \sin^2 (22.5°) \geq \frac{1}{2} \sin^2 (45°)$

Evaluating the above three terms gives:

$\frac{1}{2} (.14645) + \frac{1}{2} (.14645) \geq \frac{1}{2} (.5)$ or, $(.14645) \geq (.25)$

This *last* inequality is obviously *false*; and the sum of Aspect's first 2 tests (that is, the sum of the first two terms of Bell's Inequality—P{1,0,X} plus P{X,1,0})—is *not* equal to or greater than his result for the final test, P{1,X,0}.

Simply put, the results of Aspect's experiments solidly *confirmed* the QM predictions, but clearly *violated* Bell's Inequality…

We've covered a lot of ground in this somewhat lengthy chapter, so let's pause to summarize:

Einstein thought a dynamic attribute like a photon's polarization must exist, even *before* being measured; Bohr thought the photon's polarization didn't exist *until* it was measured.

In quantum mechanics, certain processes permit the creation of "entangled" *pairs* of quantum 'entities' (like photons, electrons, etc.). QM theory says these entangled pairs must be described by a *common* wave-function.

If a photon's polarization *isn't* objectively real *until* measured (Bohr's view), then a polarization measurement of either member of an entangled pair must 'collapse' the common wave-function of both…*no matter how far apart the two members of the entangled pair might be*. In turn, this means the polarization attribute of the distant member is *brought into existence* by a polarization measurement of the local member…again, no matter how far apart the two members may be.

Einstein's argument was that such an influence—that is, a *non-local* influence—seems to violate Special Relativity, requiring, as Einstein put it, "*spooky action at a distance*". Quantum mechanics, Einstein concluded, must therefore be *incomplete* in some way…it simply did not provide a *complete* description of physical reality.

If a photon's polarization attribute *does* exist before being actually measured—as Einstein maintained—then Bell's Inequality should be *obeyed* in experiments like that performed by Prof. Aspect.

But Aspect's experiment pretty conclusively *violated* Bell's Inequality …so "spooky action at a distance", in some sense, at least, *was* real, and Einstein, in this instance, *must be wrong.* The Universe—for quantum 'entities', at least—*is either non-local, not objectively real…or both.*

Skeptics have pointed out several potential "loopholes" in the Aspect experiments…one being the problem of "detector inefficiency" (where, for example, a photon may have interacted with a detector, but *not* been registered…or, conversely, where "noise" in the system produced a "false positive", and a photon was registered, but one *not* a member of an entangled pair).

Still another potential "loophole" was that either the entangled photon source or the polarizers on each side of the experiment were "*conspiring*"—somehow—to affect the results. Aspect lengthened the distances between the source and the two polarizers so that, even at the speed of light, any such possible "conspiracy" was eliminated. A final refinement to his experiment was to *change,* at the last possible moment, the rotation angle between the two polarizers…and the results *still* violated Bell's Inequality.

Over the years, additional improvements in technology have gradually tightened these potential "loopholes"—and others—to the extent where most physicists now agree that Bell's Inequality is, indeed, violated in these kinds of experiments.

Can this apparent "spooky action at a distance" be used for actual, *faster than light* ("FTL") communications? The answer is an emphatic *no*. Remember, the sequences of photons passing or failing the polarizers at either side of Aspect's experiment are *random*; it is only in the *correlation*—that is, in the concrete *comparison*—of the two sequences that we see any evidence of 'non-locality'. To *get* the correlations we must somehow *compare* the two separate sequences…and the fastest way this can *ever* be done is at the speed of light.

Suppose we *only* look at *one side* of Aspect's experiment, and a change is made in the rotation angle of the polarizer at the other, distant side. All we'd ever see at *our* side is one random sequence turn into a *different* random sequence…and, by definition, *all* truly random sequences look the same. Without knowing the sequence at the "far" side for comparison, you'd never know any change had been made.

Aspect's experimental tests of Bell's Inequality measured the polarization attributes of entangled photon pairs, but it was only by *comparing* the results from *both* sides of his experiment that any 'non-local' correlations become apparent.

There are, however, dynamic attributes *other* than polarization direction that we can consider…for example, the attribute of *momentum*.

In physics, there exists a phenomena called *spontaneous parametric down conversion* ("SPDC"), which can be used to create pairs of *momentum*-entangled photons. Basically, SPDC works like this: the beam from an ultraviolet laser—composed of many ultraviolet photons—is directed at a certain kind of chemical crystal (in the following example, a lithium iodate crystal is used). Each ultraviolet photon absorbed by the crystal results in *two* outgoing infrared photons, and the *sum* of the energies of these two outgoing photons is equal to the energy of the original ultraviolet photon. The two outgoing infrared photons are said to be *momentum-entangled*…each member of the outgoing pair has a momentum identical to the other, though in different directions.

In effect, the incident laser beam, consisting of many ultraviolet photons, is converted into *two* outgoing infrared beams… and every photon in either of the two outgoing beams is paired with a ‘momentum-entangled’ partner in the other.

Suppose these two outgoing infrared beams are used as the sources for two *separate* DSI experiments, as in Figure 5.1.

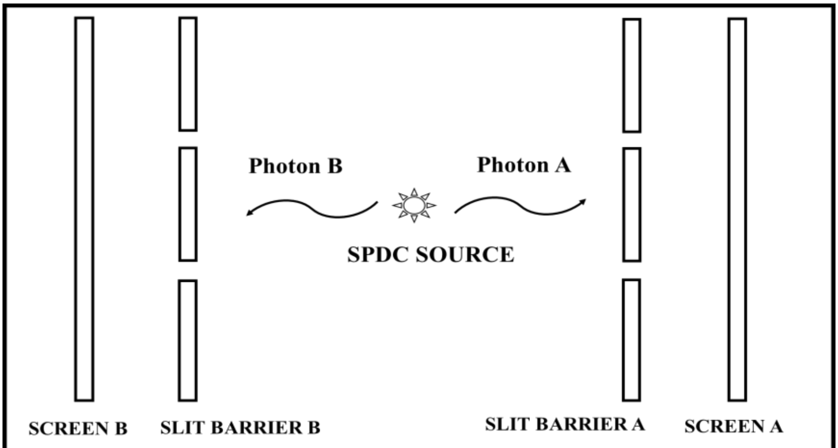

FIG. 5.1 Momentum Entangled 2-Slit Experiment

What would be observed on the two separate screens?

When all four slits are open, the familiar double-slit interference pattern is seen on *both* of the screens. Next, suppose one of the slits on side A of the experiment is *blocked* (see Figure 5.2).

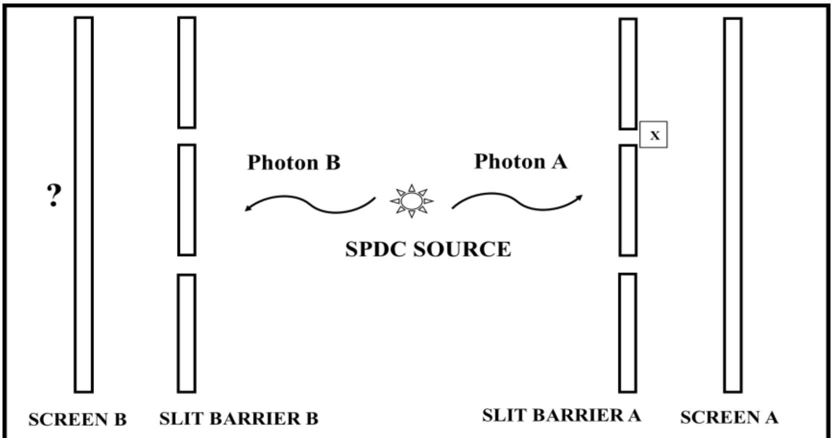

FIG. 5.2 Figure 5.1 with One Slit Blocked

Since we’d now know *which* slit any photons reaching screen A must have passed through, the pattern on screen A will change to the single-slit “smur” pattern.

But what will be seen at the *other* side of the experiment, over at screen B? Remember, our source generates *entangled* photon pairs, so each photon heading for the slit barrier on side A (labelled as photon A) is entangled with a “partner” photon — photon B—heading for the slit barrier at side B. According to QM, this entanglement means photon A must *share* a common wave-function with photon B.

Will blocking *one* of the slits on side A of the experiment *change* the pattern observed over at screen B (from a double-slit to a single-slit pattern), *even though both slits still remain open at side B?* If the wave-function associated with photon A is ‘collapsed’ by the closing of one slit on side A, shouldn’t this ‘collapse’ of the *common* wave-function affect its entangled partner—photon B— as well?

By opening or closing one of the slits on side A *only*, can we *change* the pattern observed at the screen on side B? Can we now send "Morse code" type messages from side A to side B…*no matter how far apart the two sides may be?*

No, we cannot…and here's why: when one of the slits in a DSI experiment is closed, only about *half* the number of photons will be registered on the screen, compared to the original number that would be registered if *both* slits were open. The single-slit "smur" pattern seen on side A of our hypothetical experiment must be composed of photons which have passed through the only open slit; all other photons will be *blocked* by slit barrier A.

However, *both* slits still remain open at side B. The original *number* of photons streaming from the entangled photon source has not changed, so—overall—the number of photons registered at screen B also remains unchanged. If one slit has been blocked on side A, roughly *twice* as many photons will be registered at screen B as at screen A. Only about *half* the photons registered at screen B will have their "entangled" partner photons registered at screen A.

The question is, *which* half?

By electronically monitoring both screens A *and* B—using a *coincidence detector*—we can determine *which* photons detected at screen B are *entangled* with the photons detected at screen A. Assuming both screens are roughly equidistant from the source, when a photon is detected on *both* screens—*at the same time*—we know *both* these photons were members of the *same* entangled pair. We can also note the *positions* of these *correlated* photons on screen B. Now we have a means of "filtering out" the *uncorrelated* photons registered at screen B…so we know not only *which* photons detected at screen B are entangled with photons detected at screen A, but the *positions* on screen B of these entangled photons, as well.

If we count *only* these correlated photons on screen B, we find the single-slit pattern builds up. But, if we count *all* the photons detected at screen B—*including the uncorrelated photons*—we still see a double-slit interference pattern build up.

If we look at screen B only—*without* using the coincidence detector—and a change is made on side A of the experiment, we'd never know it.

Once again, it is only by the *correlation* of the results at *both* screens that any 'non-local' effects become apparent…and such correlations can only be revealed by *comparing* the two sets of results…entangled photon pair by entangled photon pair.

Physicists have produced technical mathematical *proofs* of what are called "*no-signaling*" theorems…and no serious challenges to these proofs have ever survived.

For fans of science fiction, it really is a shame: quantum 'non-locality' *doesn't* mean we'll get faster-than-light telegraphs sending instantaneous messages between the stars…

Experimental violations of Bell's Inequality (like in the Aspect experiments) ruled out the possibility that 'quantum reality' could be *both* 'objectively real' *and* 'local', but the door remained open to 'objectively real', *non-local* models of QM (that is, *non-local* 'hidden variable' type models…like the one proposed in the de Broglie-Bohm interpretation).

But, in a 2003 paper by the British physicist A.J. Leggett, a *new* type of inequality was introduced—one differing somewhat from Bell's Inequality. Subsequent experimental violations of this 'Leggett Inequality' seemed to rule out the possibility of certain kinds of *non-local* 'hidden-variable' theories, as well. In other words, experimental violations of the Leggett Inequality suggested the de Broglie-Bohm interpretation *might* be incompatible with the proven results of QM. Additional research—by other investigators—implies this is not *necessarily* the case… so, for now at least, the de Broglie-Bohm model is still "in the running".

* * *

Most of the QM interpretations we looked at in Chapter 4—with the exceptions of the Copenhagen and Many Worlds Interpretations—involve, in one way or another, a possibly faster-than-light 'collapse' of the wave-function. And the de Broglie-Bohm interpretation *requires* its "quantum potential field" to blanket the entire Universe…*instantaneously*.

Violations of Bell's Inequality in experiments like Prof. Aspect's pretty conclusively *prove* the quantum world is somehow 'non-local' (and maybe '*non-objective*', as well). Knowing this should give us more confidence in the possibly faster-than-light implications of some of the interpretations of QM. But EPR-type experiments like this don't provide much guidance in deciding *which* of the many interpretations is right.

So, no matter which QM interpretation we choose—if *any*—we're still faced with a universe far *stranger* than anyone had ever imagined.

The Quantum Dragon is immense; its reach can span the stars. But its claws are like shadows, leaving but the faintest of traces.

CHAPTER 6

THE DRAGON’S HEART: THE NATURE OF THE WAVE-FUNCTION AND THE “MEASUREMENT PROBLEM”

“But our present [quantum mechanical] 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 omelet 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.”

—E.T. Jaynes, “*Complexity, Entropy, and the Physics of Information”*

“The concept of 'measurement' becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory at the most fundamental level... does not any analysis of measurement require concepts more fundamental than measurement? And should not the fundamental theory be about these more fundamental concepts?”

—J.S. Bell, “*Speakable and Unspeakable in Quantum Mechanics”*

Of paramount importance in formal QM theory—and in any discussion of "quantum weirdness"—is the *nature* of the wave-function…and the nature of its 'collapse' by actual measurement. How do the *many* possible outcomes of an experiment (with probabilities given by the 'Born Rule') abruptly crystallize into just *one* actually *measured* outcome? In the formal, 'orthodox' QM theory, there *is* no mechanism to account for why the *probabilities* of all but one of the possible outcomes abruptly drop to zero—and the one *measured* outcome's probability suddenly jumps to one. In its simplest terms, this *is* the "Measurement Problem" in QM.

But, first things first: what, exactly, constitutes a *measurement*?

In the "one photon at a time" DSI experiment, for instance, does the *measurement* happen when a localized flash appears somewhere on the screen, or when that flash is automatically recorded on photographic film…or when an observer first *sees* that film, perhaps many years later? In the "Schrödinger's Cat" thought experiment, does the measurement happen if—or *when*—the Geiger counter clicks, or when the cat first sniffs the poisonous gas, or when the cat's sealed container is first opened? The definition of a "measurement" is not as clear-cut as we might at first like to think…

Let's put aside, for a moment, von Neumann's insight that any "measurement" of a quantum system (like the position of a photon) *always* involves *another* quantum system (after all, phosphorescent screens, Geiger counters, etc., are *made* of quantum 'entities', too).

Many—but not all—physicists would agree that a "measurement" occurs when some kind of *irreversible* physical change takes place in the measuring instrument, whether there is an observer present or not. For example, when a photon strikes a piece of photographic film, a permanent chemical change occurs at the location where the photon has landed. This would seem to constitute a valid measurement of the photon’s position (to within a certain accuracy, at least).

But, as first pointed out by the German physicist Mauritius Renninger, sometimes information about a quantum system can be obtained *without an actual measurement* (at least as defined above) *taking place*. Consider the following “thought” experiment: a source of, say, single photons is placed at the center of a hollow, spherical detector. Each photon is emitted in a random direction, so each photon may be detected (as an individual ‘flash’) anywhere on the inside surface of the sphere.

Now, imagine a hole is punched through this spherical detector…and the size of this hole can be made as small as we’d like. When a photon is emitted from the source, it will now *either* be registered on the inside surface of the detector… *or not detected at all*. If *no* detection occurs, we must conclude that either the photon has “escaped” through the hole—or the source has “misfired”, and *no* photon was really emitted. By surrounding the *firs*t spherical detector with a *second,* larger, outer spherical detector we can eliminate this second possibility. See Figure 6.1, below.

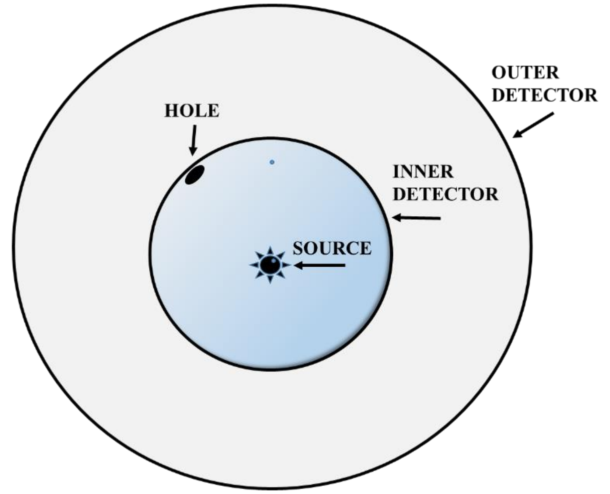

FIG 6.1 The "No-Measurement" Experiment

If the size difference between the two spherical detectors is sufficiently large, and the radius of each detector is known, we can predict the different travel times required for a single photon to reach either detector. If the photon is *not* detected on the smaller, inner spherical detector by the required travel time, we know it must have "escaped" through the small hole.

Since we know the position of the hole, we can then *deduce* the escaping photon's *position* on the inner detector (to an accuracy of the diameter of the hole)… *before* any actual "measurement" is made at either detector. In other words, the wave-function describing the *position* of the photon must have 'localized'—at least to some degree—permitting the photon's escape. (Obviously, the larger the hole, the more photons can escape through it). *But the hole is simply empty space*…yet somehow this empty space causes the 'localization' of the wave-function.

Registration of the photon on the outer spherical detector—at a later time—simply *confirms* the photon's escape through the hole. And the *position* of the photon's detection on the outer detector is, once again, a question of probabilities…as described by a wave-function. In short, the wave-function describing the photon's position on the inner detector must 'localize', allowing the photon's escape through the hole, but then—*somehow*—be reconstituted, 'collapsing' at a later time when the photon is registered at some definite position on the outer detector…

"Renninger-style" thought experiments like this serve two purposes: they illustrate not only the ambiguous nature of the "Measurement Problem" in formal QM theory; they also provide some insight into the nature of the wave-function itself.

Generally speaking, there are two schools of thought regarding the QM wave-function. One viewpoint treats the wave-function as being *epistemological*—that is, the wave-function simply represents our *knowledge* of the 'reality' underlying QM. The other viewpoint is that the wave-function is *ontological*—that is, the wave-function itself *is* the underlying 'reality'.

A somewhat basic illustration of epistemology vs. ontology can be found in a two-player version of the card game known as "Blackjack", or "21". From a standard, well-shuffled deck of 52 cards, you and your opponent are each dealt 2 cards—one face up, the other face down. Obviously, the values of the two face up cards are known to both players…but the values of the two face down cards are *not*.

In an *epistemological* interpretation of this game, you must treat the value of your face down card on a strictly probabilistic basis: although it *cannot* be either of the face up cards held by you or your opponent, it *might* be any one of the 50 unknown cards still left…so, the probability of your face down card being any *specific* card is 1/50. This same reasoning applies to the other player's hand, as well.

Suppose your opponent is first to show their face down card. The *probability* of your face down, unknown card being a specific value has *changed*: it cannot be any of the 3 cards now showing. The new probability for your face down card having a specific value becomes 1/49. Your opponent's 'reveal' of their face down card *has changed the probability of your unknown card*. In an epistemological treatment, the other player's reveal of their hidden card has changed your *knowledge* of the situation…but it is only when you reveal *your* face down card that your knowledge becomes complete.

An *ontological* view of this game is different: the hands dealt to you and the other player consist of objectively real cards, with every card having a definite, fixed value, including the cards dealt face down. Your *knowledge* of these values may change…but the cards themselves *do not*.

Consider, once again, the "Schrödinger's Cat" experiment. If the wave-function is just an epistemological description, the cat, *in reality*, is always *either* dead *or* alive. In the epistemological view, the QM wave-function describes our *knowledge* of the cat's condition. Before the container is opened, this knowledge must be represented as a superposition of *both* states, and—because our knowledge at this stage is limited—we must regard the cat as being both dead *and* alive, with various probabilities. Performing an act of measurement (by opening the container, and observing the cat) sharpens our *knowledge* of the situation…and the epistemological wave-function 'collapses'.

An epistemological view of the wave-function also clarifies the "quantum weirdness" raised by the "Wigner's Friend" extension to the "Schrödinger's Cat" experiment. Wigner's friend, who has remained outside the closed room, has knowledge of a *different* kind than the first observer. For this second observer, the epistemological wave-function has not yet collapsed…and won't, until they see for themselves how the cat is doing (or are informed of its health by the first observer).

At first glance, the epistemological view of the QM wave-function also seems to fit nicely with Born's *statistical* interpretation of the wave-function. (Recall the "Born Rule", which states the probability of finding a photon, electron, etc. at a specific location is given by the absolute value of the *square of the amplitude* of the wave-function at that location). Until actually *measured*, the position of an electron, for example, is indefinite and probabilistic…it *might* be here, or it *might* be there, with various probabilities. An *epistemological* understanding of the wave-function sees this as a limitation of our *knowledge* of the electron's position. As with "Schrödinger's Cat" (where, in reality, the cat is *either* dead *or* alive—but never *both*), the electron, in *reality, does* have a definite position…it's just that, until actually *measured*, we simply won't know what it is. But this is in direct conflict with Bohr's interpretation of QM theory, which tells us—in effect—it is the *act of measurement itself* which *creates* the electron's position.

It is here we run into difficulties with the "epistemological" interpretation of the wave-function.

The first problem is that of *measurement*. Recall the "no-measurement" thought experiment described above. It demonstrates that, in certain circumstances, the position of a photon can be *deduced*, even *before* an actual detection has taken place. If the wave-function is epistemological in nature, how can such a *non-measurement* change our knowledge of the situation? How can a *non-measurement* cause an epistemological wave-function to '*collapse*'? Either we must drastically change the definition of "measurement" mentioned earlier in this section …or we must re-consider the epistemological view of the wave-function.

Yet another problem with an epistemological view of the wave-function arises in the "one photon at a time" DSI experiment. Recall from Chapter 1 that, in this experiment, the wave-function apparently passes through *both* slits, then *interferes* with itself—in a very well-defined manner—on its way to the screen. Furthermore, the wave-function must change if the experimental setup is altered in any way (if one of the slits is closed, for example, or the slit-barrier to screen distance is changed, etc.…). The experimental set-up can apparently *act* on the wave-function. And this applies not only to a wave-function representing a beam composed of many photons, but to a wave-function representing a *single* photon, as well. The results of the DSI experiment are demonstrably statistical: any given *single* photon *might* appear anywhere on the screen (Refer back to Image 1, in Chapter 1). But, with both slits open, there is a statistical *tendency* for the photons to "cluster"—*one photon at a time*—where the bright fringes of the interference pattern appear on the screen. As the number of individual photons registered at the screen increases, the fringes become more and more pronounced.

Like a "loaded" coin, which might "tend" to land on 'heads' a little more often than 'tails', each single photon in the DSI experiment has a *tendency* to appear in one of the bright fringe zones. And, as with a "loaded" coin, we might expect there to be an underlying *physical* reason for *each* photon's *tendency* to behave in this "wave-like" manner. In an epistemological view of the wave-function, it is difficult to see how our *knowledge* of the situation can play this role.

Next, consider an *ontological* interpretation of the wave-function. In an ontological interpretation, the wave-function does not represent our *knowledge* of the physical reality of a quantum system—it *is* the reality. The very same arguments used to *dispute* the epistemological view can be used to *suppor*t an ontological view…but the converse is true, as well.

For example, in the "Schrödinger's Cat" experiment, instead of an *epistemological* wave-function representing our *knowledge* of the cat's state before the container is opened—where the cat is, *in reality*, always either dead *or* alive—the ontological interpretation of the wave-function insists the cat, in reality, *does* exist in a superposition of states; the cat is both dead *and* alive, until its state is measured…by opening the container, and looking. In the double-slit experiment, an *ontological* wave-function goes through both slits, interferes with itself, and so produces the wave-like interference pattern seen on the screen. Adopting an ontological view of the wave-function leads right back to the "weirdness" of the "Schrödinger's Cat" and "Wigner's Friend" experiments, yet *seems* to eliminate some of the "weirdness" of wave/particle duality in the DSI experiment.

But, in the DSI experiment, we still face a variation of the "Measurement Problem": it is only *between* actual "measurements" of the photon's position that each photon exhibits a *tendency* towards "wave-like" behavior (by *tending* to be eventually detected as a single flash in one of the bright interference fringes on the screen). Whenever *actually* registered on the screen, though, each individual photon always reveals itself as a single, "particle-like" flash. Formal QM theory has no mechanism for describing this 'collapse' of an *ontological*—that is, physically *real*—wave-function to a single, apparently particle-like detection at the screen. Again, we have a dilemma: if—*between measurements*—the 'reality' of a single quantum 'entity' *is* the wave-function, how—and *why*—does this wave-function 'collapse' to a single, localized, apparently particle-like *thing* (like a single photon, or single electron) when detected?

Consider again the "no measurement" experiment shown in Figure 6.1, above. If the photon is *not* detected on the inner spherical detector, we know it must have "escaped" through the hole. If the wave-function is *ontological*, this means it must have 'localized'—at least to some degree—when passing through the empty space of the hole. But why should a “non-measurement” like this collapse an ontological wave-function, even before an *actual* detection of the photon has occurred? Even more confusing, if the wave-function corresponding to the photon’s position has ‘collapsed’ when the photon “escapes” through the small hole, it must—somehow—be *reconstituted*; the photon will subsequently be registered on the outer, larger spherical detector at just *one* of *many* possible positions— given by *another* wave-function.

Do “EPR-type” experiments help us choose between the ontological and epistemological interpretations of the wave-function? As we saw in the previous chapter, the violation of Bell’s Inequality in, for example, Prof. Aspect’s entangled photon polarization experiments, pretty conclusively proved that the quantum ‘world’ is *non-local*…and this would seem to support an ontological view of the wave-function. When the *common* wave-function of the two entangled photons is ‘collapsed’ by a measurement made at one side of the experiment, it can affect measurements made on the “entangled” partner photon…no matter how far apart the two entangled partners may be. But other issues with an ontological interpretation of the wave-function—as detailed above—still persist.

Fairly recent experiments, in conjunction with so-called “no-go” mathematical theorems, *seem* to favor an ontological view of the wave-function…but the issue, nevertheless, remains far from settled.

Suppose, in our previous example of a card game, the game was hypothetically governed by an *ontological* version of quantum mechanics. If this were the case, when the other player revealed their face down card, the actual *value* of our hidden card could *change*.

Other, less ‘orthodox’ interpretations of QM provide ways out of this ontological vs. epistemological dilemma…

The various types of “Many Worlds” interpretations, for example, sidestep both the “collapse” and “measurement” problems *completely*: the nature of the wave-function *transcends* both the ontological and epistemological categories. Because the wave-function *neve*r collapses, *all* the results of a given experiment occur. But, in the “Many Worlds” interpretations, a single photon in the DSI experiment *still* tends to be detected in just *one* of the interference fringes—although *which* fringe depends on which of the many “worlds” we happen to find ourselves observing it *in*.

In the “de Broglie-Bohm Quantum Potential Field” interpretation, the wave-function *itself* is re-expressed in a different mathematical form. The wave-function is shown to be equivalent to *two* separate, ontologically ‘real’ expressions: one familiar as describing an ordinary particle, and the other describing an extraordinary ‘quantum potential’ *field*. This field *steers* each quantum particle along a specific trajectory. In the de Broglie-Bohm interpretation, a single photon, for example, is always regarded as a *particle*, and one that always has both a definite position and trajectory…although, until measured, these must remain unknown to us. For the DSI experiment, each photon’s trajectory is guided by the ‘quantum potential’ field, which “senses” (perhaps *instantaneously?*) the state—open or closed—of *both* slits, then guides each photon into the appropriate pattern. And, in “EPR-type” experiments, the non-local nature of the ‘quantum potential’ field is an advantageous *feature*. But the apparently *instantaneous* nature of this field, and its *unmitigated* strength at any distance, is still viewed with skepticism by many physicists.

The Quantum Dragon’s heart is strong—its pulse is the essence of the beast. But, between each beat, is the Dragon even real?

CHAPTER 7

THE DRAGON’S TAIL: SOME FINAL THOUGHTS REGARDING PART 1

In July, 2011, a conference titled “Quantum Physics and the Nature of Reality” was held at the International Academy Traunkirchen in Austria. Afterwards, the 33 participants (mostly physicists, but including mathematicians, philosophers and computer scientists) completed a “snapshot” multiple-choice questionnaire regarding their opinions on the foundations of quantum mechanics. Most interesting were the responses to the question: “What is your favorite interpretation of quantum mechanics?” Although the Copenhagen Interpretation was the front-runner (at 42%), the remaining 58% of responses were quite mixed. Write-in comments were encouraged on the questionnaire; some of my favorite individual responses were to the questions “How often have you changed your preferred interpretation?” (*“At least several times a day”*), and, “In 50 years, will we still have conferences on the foundations of quantum mechanics?” (*“I hope not”*). Admittedly, the survey was very informal, with a limited sample size. Other, more recent conferences on the “foundations of quantum mechanics” have been held—some with a greater number of participants—but *all* had similar outcomes: there still exists no *consensus* opinion on the nature of ‘quantum reality’.

Does the fact that so many professionals in the field hold such disparate views on the very *foundations* of QM theory constitute an actual *crisis* in physics? Not at all; formal QM theory remains—so far, at least—unchallenged in its success. But active debates—and questions—about the *meaning* of the theory continue to this day.

In Part 1 of this book, we've looked closely at just two experiments, and the "quantum weirdness" which goes along with each. There are, of course, many, many more such experiments…and many other examples of "quantum weirdness".

The DSI and EPR-type experiments provide undeniable proof that the everyday world in which we live is not so "everyday" after all. And the manifestations of "quantum weirdness" we've looked at so far aren't remote, abstract ideas, found only in the cosmic or sub-atomic realms. The "weirdness" is all around us, all of the time. In fact, it is even found *within* us, since we are *made* of quantum 'entities'.

In the DSI experiment—it seems to me, anyway—there are four major unanswered questions:

What goes through the slits?

What—if any—is the *physical* nature of the wave-function?

And what, exactly, causes its 'collapse'?

What is the *physical* meaning of the de Broglie wavelength?

Unless you accept the Copenhagen Interpretation—which regards these questions as *meaningless*—not one of these questions has truly been resolved. And you can't really answer the second, third or fourth questions until you've settled the first.

* * *

Turning to Aspect's version of the EPR experiment, we've seen proof that, for quantum 'entities', the Universe is, at the very least, somehow *non-local*. But the only thing to be said for sure about this EPR non-locality is that *we* can't use it for instantaneous “communication”, but nature certainly can…and *does*.

What, then, is the underlying *nature* of EPR non-locality? What makes it so all pervasive, and yet so private? Is it some intrinsic feature of the QM wave-function? Or is it, perhaps, the only *observable* manifestation of the de Broglie-Bohm “quantum potential field”?

As matters stand today—and despite ongoing research—*no one really knows*…and so the debates continue.

* * *

Quantum mechanics has proven itself, time and again, to be an absolutely *amazing* resource. It’s like having a cookbook for solutions to all kinds of physics problems…including problems that, for pre-quantum physics, were completely intractable. As I’ve tried to emphasize throughout this book, QM—so far, at least—*works*. *Always*. But some of the ingredients found in the ‘recipes’ have pretty mysterious backgrounds.

To date, QM theory has served as an infallible guide when used for both theoretical and practical applications…but what, exactly, does it *mean?*

If questions like these don’t trouble you at all, or you’re already comfortable with one of the many, many interpretations available, there’s not much point in proceeding to Part 2 of this book.

If, on the other hand, you find yourself somehow—*dissatisfied*—with the answers given so far, by all means, read on...

PART 2: CONFRONTING THE DRAGON

INTRODUCTION TO PART 2

> *"Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has escaped. Nobody knows how it can be like that."*
>
> —Prof. Richard Feynman

Is this some kind of ominous warning, like *"Here be monsters*" or "*Abandon all hope, ye who enter*"? If so, shouldn't we take it seriously? After all, we followed Feynman's advice once before, way back in Chapter 1, so why disregard it now? *Should* we continue asking naïve, apparently unanswerable questions like *what goes through the slits?*

Feynman himself developed some pretty unusual methods for doing QM, like the "Sum Over Histories" approach. And the various interpretations of QM we looked at in Chapter 4 came about, to some degree, from the theorists' own desire to understand the *physical* basis of QM theory.

In the following chapters, "toy" *models* of the DSI and EPR experiments are presented. These models are in *no way* intended as a substitute for, or an improvement upon, conventional QM theory…nor should they be considered as new *interpretations* of QM, either. Instead, they are presented simply as alternative ways of—perhaps—*visualizing* the underlying "reality" of these experiments…strictly within the context *of* these experiments.

And, hopefully, these “toy models” just might demonstrate that *all* the possibilities for interpreting QM theory have yet to be exhausted.

We’re not physics students here—there’ll be no final exam—so perhaps we, too, can afford the luxury of a little speculation…

CHAPTER 8

THE DSI EXPERIMENT: *What Goes Through the Slits***?**

Most of the interpretations we've looked at so far have answered our question—*what goes through the slits?* —by saying that it is *something else*…a *something* existing only at the quantum scale, and so a *something* completely unfamiliar to us in our macroscopic world. Most, but not all, physicists accept this idea—and for *very* good reasons, as we've seen. Nature, of course, is under no obligation to satisfy human expectations of what 'reality' *should* be like.

However, the stubborn fact remains: there's still *no consensus answer* to our question—"*what goes through the slits*?" As we've already seen, attempts to answer this question lead straight into the "paradox" of wave/particle duality…

Clearly, in the double-slit interference experiment, *something* goes through the slits…but the nature of that *something* remains problematic.

A 'conventional' wave won't do, because at very low intensities, *individual* flashes are registered on the screen…not the very dim interference pattern we'd expect 'conventional' waves to produce. It's also difficult to reconcile a wave-based model with quantum 'entities' (such as electrons or protons), which have additional, highly *localized* attributes, like charge and rest-mass. How, for example, would discrete electric *charge* be distributed in a 'conventional' wave-like model? Yet charged particles—like electrons and protons—*do* build-up a wave-like interference pattern in the DSI experiment…even when dealing with just a single particle at a time.

But our mysterious *something* cannot be a ‘conventional’ particle, either. If it were, we wouldn’t see an interference pattern build up over time at very low intensities…*yet we do*.

A *modified* particle model, on the other hand, seems to have definite possibilities…

In fact, as we saw in Chapter 4, the de Broglie-Bohm “Quantum Potential Field” interpretation very successfully presented a particle-based model…one that seems to be completely consistent with both formal QM theory and all experimental results. One reason this model wasn’t quickly adopted by many more physicists, though, was its inclusion of the ‘quantum potential field’—a field completely unlike any other known to physics. This field apparently *instantaneously* permeates the entire universe, and its strength remains absolutely *undiminished* with distance.

Might it be possible to construct a consistent “toy” model of our mysterious *something* by a physical re-interpretation of one of the elements *already* present in the ‘formal’ quantum theory itself? The objective of such a “toy” model would be to reproduce the experimental results of the DSI experiment (specifically, the interference fringes observed on the screen)—without the need for any *waves* at all.

Perhaps we can kill two birds with one stone here. In Chapter 1, besides asking “*what goes through the slits?”*, we also asked: “*what could be the physical meaning of a particle’s de Broglie wavelength?*”

We need to get very specific now, so it’s time for some math…

The de Broglie wavelength of a particle is given by:

(Eq. 8.1) $$\lambda = h / mv$$

where λ is the de Broglie wavelength, h is Planck's constant, m is the particle's mass, and v is the particle's velocity. The product, mv, is the particle's momentum.

Let's introduce a concrete, *physical* interpretation of the de Broglie wavelength, and see if it can help explain the *emergent* wave-like behavior seen in the DSI experiment:

> *The de Broglie wavelength of a particle is the discrete, minimum distance across which that particle can move.*

We can call this the discrete motion interpretation ("DMI") of the de Broglie wavelength.

(A potential source of misunderstanding here is the use of the term "wavelength". Although originating in the wave-like model developed by de Broglie, a particle's "wavelength" is a physical quantity always measured in units of *distance*…that is, in meters or yards, inches, or angstroms).

What DMI implies—in terms of *physical* reality—is that the particle (photon, electron, etc.) only *exists* at the endpoints of each discrete, wavelength-long "jump". It can only influence—or be influenced by—the external world at these endpoints.

An immediate corollary to this DMI interpretation is:

> *An un-accelerated particle's total trajectory length must be an integer multiple of its de Broglie wavelength.*

Mathematically,

(Eq. 8.2) $T = N\lambda$

where T is the particle's *total* trajectory length, and N is an integer.

In this particle-based DMI model, the assumption of *continuous motion* has been intentionally *discarded*; instead, quantum particles (photons, electrons, etc.) *jump*—so to speak—from point to point along their trajectories, with each 'jump' being a discrete distance, one de Broglie wavelength long.

From a distance, or at a large enough scale, these DMI-type trajectories *appear* to be continuous…much like a fine jewelry chain, composed of tiny, equal-sized links, would appear to be a continuous length of wire, when viewed from a distance. The particle only 'exists' at the endpoints of its wavelength-sized jumps. When a particle is detected, for example, at a location on the screen, the DMI model *insists* this must occur at the *endpoint* of a DMI-type trajectory.

How does a particle "*know*" to follow a DMI-type trajectory to the screen? It does not. In the DMI model, if a particle follows a *non*-integer trajectory to the screen, it is simply not detected. (Of course, moving the screen closer or farther away by less than one de Broglie wavelength might have allowed *that* particle to be detected; *other* particles would have then gone undetected).

Another immediate corollary to DMI is that the *difference* between any two allowed DMI trajectories must *also* be an integer multiple of wavelengths:

(Eq. 8.3) $T_a - T_b = n\lambda$

where T_a is the length of one of the DMI trajectories, T_b is the length of the other DMI trajectory, and n is an integer. (Typically, n will be *much* smaller than the N from Equation 8.2).

By dropping the assumption of continuous motion, the DMI model *restricts* the number of possible trajectories a particle can follow from the source, through one slit *or* the other, to the screen. Will this modify the ‘conventional’ particle model in such a way that the “wave-like” interference behavior at the screen becomes emergent? Apparently it does, as we’ll see…

Long before quantum mechanics was developed, physicists had worked out a very successful, wave-based model of light (as shown in Young’s original DSI experiment). The mathematics of this “classical” wave-model is still valid, and is incorporated into the QM description of the DSI experiment.

A simple rule from the “classical” wave-model tells us exactly where we’ll find bright and dark interference fringes on the screen. Figure 8.1 is a diagram of the DSI experiment (the figure is not drawn to scale).

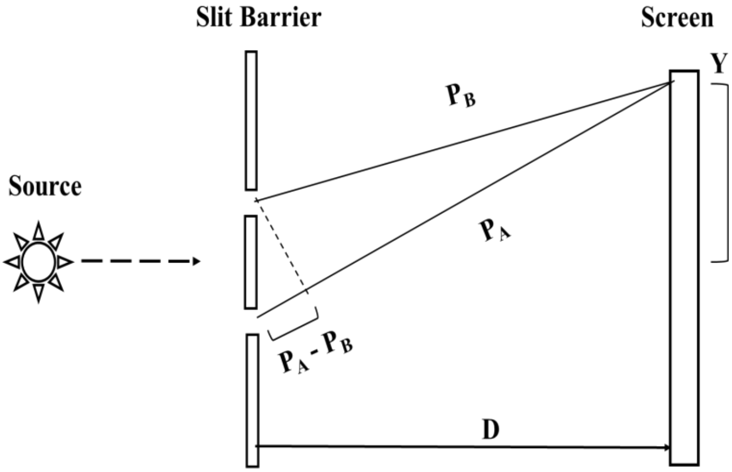

FIG. 8.1 DSI Wave Maxima and Minima

If the *difference* between the two paths from the slits to a point, P_Y, on the screen is an *integer* multiple of wavelengths, there will be a bright fringe at that point. If the difference is a *half*-integer multiple of wavelengths, a dark fringe will be observed.

Mathematically:

(Eq. 8.4) $(P_A - P_B) = n\,\lambda$ Condition for a bright fringe at P_Y

(Eq. 8.5) $(P_A - P_B) = (n + ½)\,\lambda$ Condition for a dark fringe

where n is an integer (like 0…1…2…3…etc.), P_A is the path length from one slit to a point, P_Y, on the screen, and P_B is the path length from the *other* slit to the point P_Y. D is simply the distance from the slit barrier to the screen.

Equation 8.4— the “classical” wave-model condition for a bright fringe at a point, P_Y, onscreen—is *identical* to the difference in

DMI trajectories given in Equation 8.3. The same condition—that, for a bright fringe, the path *difference*, (P_A – P_B), be an *integer* multiple of wavelengths—applies to both the “classical” wave-model and the DMI particle-based model. The same results are obtained, but from very *different* physical models.

The bright fringes, are, after all, what count—because that’s where the action is. The dark fringes just show us where light—even as individual photons—has a low probability of reaching the screen.

So far, so good. Our tentative, particle-based DMI model of the DSI experiment gives us the correct locations for the bright fringes on the screen… unfortunately, though, it does not give them *all*.

In the “classical” wave-model, there can exist *non*-integer paths from the slits to a point on the screen (for example, 998.7 wavelengths…1020.7 wavelengths, etc.). Even though the path *lengths* themselves *aren’t* integer multiples of the wavelength, the *difference* between them can be (for instance, 1020.7 wavelengths *minus* 998.7 wavelengths = *22* wavelengths)…and we’d see a bright fringe on the screen.

Since our tentative DMI model cannot account for this situation, it must be, in some way, *incomplete*. Can this shortcoming be addressed?

In the “classical” wave-model, when both slits are open, each individual wave from the source encounters the slit barrier, and is split into *two* component waves. Each slit now acts as a *new* wave source. Because both component waves are derived from the same, original source wave, peaks and troughs in the two component waves will occur at the same time…they are synchronized, or, as physicists might say, the two component waves traveling from the slits to the screen are “in-phase”, or “phase-coherent” —as illustrated back in Figure 1.3.

In the “classical” wave-model, the path lengths from the slits to a point on the screen are measured from the *front*, screen-facing “surfaces” of the slits—that is, from an *imaginary* surface boundary extending across the face of each slit. In reality, of course, the slits themselves are nothing but empty space…

The DMI model, on the other hand, treats quantum entities (photons, electrons, etc.) as being, at all times, real, individual *particles*. In the DMI model, these particles can only follow allowed, DMI-type trajectories, and these trajectories are followed all the way from the *source*, through one slit *or* the other, to the screen. The chances are very slight that the imaginary front “surface” of the slit will coincide *exactly* with the endpoint of a DMI “jump”. Should the starting point for a *particle’s* DMI trajectory from the slit to a point on the screen be considered *unknown* to within 1 wavelength of the slit’s front “surface”? After all—and by definition—in the DMI model we’re measuring trajectory lengths with “rulers” marked off in increments of 1 de Broglie wavelength. Such rulers can *only* measure a trajectory’s distance to within a precision of one de Broglie wavelength.

In cases where the path lengths from the imaginary front “surfaces” of the slits to the screen are *non-integer* multiples of the de Broglie wavelength, it’s possible we’re not measuring the *complete* length of a DMI slit to screen trajectory, because we’re not including the offset distance *within* the slit of the DMI trajectory’s starting point.

In the “classical” wave-model, the length from the *imaginary* slit surface to the on-screen point can *always* be expressed as a multiple of the de Broglie wavelength, with two parts: an integer part, and a *sub*-integer part. (In the earlier examples given, a “classical” wave-model path length of 998.7 wavelengths has an *integer* part of 998 wavelengths, and a *sub-integer* part of .7 wavelengths; the path 1020.7 wavelengths long has an *integer* part of 1020 wavelengths, and a *sub-integer* part of .7 wavelengths).

But, in the “classical” wave-model, a bright fringe can only appear on the screen when the *difference* in the path lengths from the two slits is an *integer*…and this condition can *only* be met when the *non-integer* portions of the two path lengths are the *same*. (In the example just given, both of the “classical” path lengths have a *sub-integer* component of .7 de Broglie wavelengths).

Suppose—in the DMI model—each time a particle passes through a slit, it is accompanied by a *random*, definite, but *unknown* offset of the DMI trajectory’s “start” point *within* the slit. When this random, non-integer offset—which is *always* less than 1 de Broglie wavelength—happens to be “balanced” by the *sub*-integer portion of the “classical” wave-model path length, a valid DMI-type trajectory exists. Using the example values given above, the *sub-integer* components of the “classical” wave-model path lengths are both .7 wavelengths. If the DMI offset within the slit randomly happens to be .3 de Broglie wavelengths, the sum of the DMI offset and the sub-integer component of the “classical” wave path length is 1 wavelength…so a DMI–type trajectory exists.

Let’s now compare the “classical” wave-model of the DSI experiment to our *extended* DMI model for a double-slit interference “event”—that is, the detection of a *single* flash on the screen. A large number of such events, recorded over time, accumulate to form the interference pattern.

In the “classical” wave-model, each individual *wave* from the source strikes the slit barrier, where it passes through *both* slits, resulting in *two* waves traveling on towards the screen. These two resultant waves then interfere with one another, producing the light and dark interference fringes. (Refer back to Figure 1.3).

Unlike ordinary waves, however, the QM waves are, in a sense, waves of *probability*. After interfering with itself on the way to the screen, the QM wave "collapses" to just a single point, where it's detected as a single 'flash' of light.

The amplitude of the QM probability wave can, at times, assume *negative* (or even *imaginary*) values. To get the probability of detecting the particle at any point on the screen, we apply the "Born Rule": we take the absolute value of the *square* the amplitude of the probability wave at that point. This avoids the awkward situation of dealing with a *negative* (or possibly even an *imaginary*) probability, ensuring the probability is *always* positive.

The DMI model, on the other hand, assumes a single *particle* passes, randomly, through just one slit or the other. *Which* slit, however, must remain unmeasured—otherwise, the interference pattern will *disappear*. Each particle just randomly follows *one* of the many *possible* DMI trajectories—from the source, through one slit *or* the other—and on to the screen. When *both* slits are open, there are more of these possible DMI trajectories available… so statistically there's a greater chance the particle will be detected where the endpoints of these available DMI trajectories either cluster or coincide on the screen.

In fact, the DMI trajectories cluster or coincide *exactly* where the bright fringe positions are predicted by the "classical" wave-model…and where they are experimentally observed. Over a *large* sample of events, more particles will be registered where more allowed DMI trajectories cluster or coincide at the screen; at such places, a bright interference fringe will build up.

Our “toy” DMI model, then, agrees mathematically with the “classical” wave-model condition for bright fringes on the screen. Changes in the experimental set-up (opening or closing one of the slits, for example, or changing the separation distance between the two slits) alters the pattern observed on the screen…because all that is really changing is the availability and endpoint locations of the allowed, DMI-type trajectories.

Generally speaking, trajectories are *geometric* in nature…they have no real *physical* existence until a particle actually follows one. Changes and interactions among such geometric entities can, of course, be instantaneous—that is, *non-local*—since no real, *physical* forces or objects are involved.

(As a simple illustration of this distinction, consider a Pythagorean triangle formed by the *height* of, say, a nearby building, the *baseline* of your distance from that building, and the *hypotenuse* length of your sight line to the top of the building. Suppose you abruptly shift your gaze slightly upward from the building’s roof to a star in the sky just above it. The *hypotenuse, baseline, and height* of the triangle have just increased—in less than a second— from perhaps several hundred *feet* to several *light-years*…but nothing *physical* has happened—only the abstract, *geometrical* sides of the triangle have changed).

In the DSI experiment, the generalized, “classical” wave-model equation for the positions of the bright fringes on the screen (refer back to Figure 8.1) is given by:

(Eq. 8.6)
$$Y_m = \frac{m\lambda D}{S}$$

where Y_m is the position of a bright fringe on the screen, D is the distance from the slit barrier to the screen, S is the separation between the two slits, λ is the wavelength, and m is an integer (such as 0…1…2…3…etc.).

The central bright fringe (the so-called “zeroth” fringe) appears when m = 0, at position Y = 0 on the screen; the next bright fringe appears when m = 1, at position Y_1 on the screen…and so forth. Equation 8.6 simply says the m^{th} bright fringe appears at position Y_m on the screen.

The *particle*-based “toy” DMI model also yields this same result…and so agrees with both experiment and QM theory.

What of the other two experiments we looked at back in Chapter 1? Can the “discrete motion interpretation” model account for the “single-photon interference” experiment diagrammed in Figures 1.4a and 1.4b?

In the DMI model, the photon is *always* regarded as being particle-like, and the two paths available to it (as shown in Figure 1.4b) are regarded in the same way as the slit to screen path lengths in the DSI experiment. When the mirror in Figure 1.4b is moved up or down, the length of path B is *changed*; when path B’s length is an *integer* multiple of de Broglie wavelengths, there are more allowed DMI-type trajectories a photon can follow to the detector; when path B is a *non-integer* multiple of de Broglie wavelengths, only photons following DMI-type trajectories along path A can be detected.

For the Pfleegor-Mandel “Two-Source” experiment (refer to Figure 1.5), this same reasoning applies. Instead of picturing a single photon “co-produced” by the two independent sources, the particle-based DMI model regards the two independent lasers as being somewhat like the two slits in the DSI experiment. When the path lengths from the two sources are integer multiples of the de Broglie wavelength—that is, DMI-type trajectories—there are more ways available for individual photons produced by *either* laser to reach the detector, and an interference maximum is observed.

By providing a concrete, *physical* interpretation of the de Broglie wavelength, the particle-based “toy” DMI model can account for the “wave-like” interference pattern actually observed on the screen. The double-slit interference pattern is seen to be an emergent, statistical result of DMI imposed restrictions on the trajectories a particle can follow.

The “toy” DMI model answers our question, “*What goes through the slits*?” with the following: a *particle does*, and that particle *always* passes through just one slit *or* the other. The ‘non-local’ aspect of the DSI experiment (that is, how a particle passing through just one slit can “know” whether *both* slits are opened) is seen to be *geometrical*, and not physical, in nature.

But the DMI model has its *disadvantages,* too. Discarding the assumption of continuous motion is a pretty dramatic step, one with far-ranging consequences for not only quantum mechanics, but many other areas of physics as well.

CHAPTER 9

THE SINGLE-SLIT INTERFERENCE EXPERIMENT: *What Goes Through the Slit?*

Back in Chapter 1, the description of the single-slit "smur" pattern was deliberately over-simplified. It is, in fact, more complex, being itself composed of a faint interference pattern, and it is this phenomena of single-slit interference (SSI)—also known as single-slit *diffraction* — to which we turn next.

The progression here may seem somewhat out of sequence; you might have expected the single-slit experiment to be dealt with *before* the double-slit experiment. The reason for addressing the experiments in this "reverse" order will shortly become clear.

When closely observed, the single-slit "smur" pattern resolves itself into a series of bright and dark bands on the screen—an interference pattern. Just as in the DSI experiment, when the source intensity is *very* low, this pattern builds up, individual flash by individual flash, over time.

In Chapter 8, we saw how the particle-based "toy" DMI model can accurately predict the existence and location of the bright interference fringes seen in the DSI experiment. Can this speculative DMI model also account for the phenomena of single-slit interference, as well?

The "classical" wave-model neatly accounts for single-slit interference: the slit acts as a source of an infinite number of "wavelets", each propagating outwards towards the screen. These wavelets can interfere with one another, and this interference results in the pattern of fringes observed at the screen. As with the DSI experiment, the "classical" wave-model once again provides a simple rule for predicting where the bright fringes will appear.

Figure 9.1 shows a diagram of the SSI experiment (again, the figure is *not* drawn to scale).

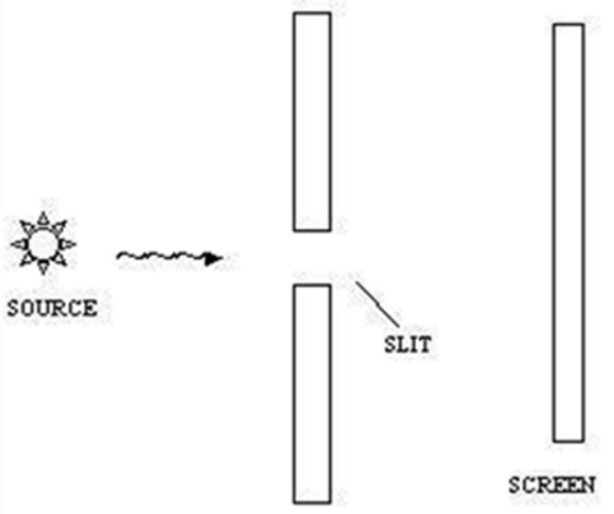

FIG. 9.1 **The Single-Slit Interference Experiment.**

Consider a point, P_Y, somewhere on the screen, and the two paths leading to it from the *uppermost* and *lowermost* edges of the slit. If the difference between these two path lengths is *half* an integer number of wavelengths, a bright fringe will be seen at the point, P_Y. If the path difference is an *integer* number of wavelengths, a dark fringe is seen at point P_Y. (Oddly enough, these are somewhat the *opposite* of the rules used for determining the double-slit interference fringes, given in Equations 8.4 and 8.5).

An *exception* to this occurs when the difference between the paths from the upper and lower *edges* of the slit to the center of the screen is 0; in this case a *bright fringe* is observed at the center of the screen).

In the “classical” wave-model, each original source *wave* passes through the *entire* slit at once, and the wavelets are created across the entire slit “surface”...but, as in the DSI experiment, this “surface” is *imaginary*, and the slit itself is nothing but empty space.

To be consistent with our particle-based “toy” DMI model, however, each point-like *particle* can only pass through one small part of the slit—let’s call it a “sub-slit”—on its way to the screen.

If the entire slit is of width, W, and the sub-slits are considered as being of equal widths, the number of sub-slits will be:

(Eq. 9.1) $\#sub_W = W/w$

where $\#sub_W$ is the *number* of sub-slits contained within the *entire* slit; W is the *entire* slit width, and w is the width of *each* individual sub-slit.

Note we’ve left the actual value of each sub-slit width, w, *unspecified*…it can be made as small as we’d like, vanishing, if we choose, towards 0. As we let w approach 0, the number of sub-slits increases.

Assuming the chances of any given particle passing through any particular sub-slit are both random and equal, the *probability*, P_s, the particle passes through any *particular* sub-slit is:

(Eq. 9.2) $P_s = 1/\#sub_W$ or $P_s = w/W$

With each particle passing through just a *single* sub-slit, though, there's no obvious mechanism to generate the interference pattern observed, unlike in the DSI experiment.

Now, a striking feature of the SSI experiment is the omnipresent symmetry between the upper and lower halves of the interference pattern on the screen. If we try to, say, *eliminate* the lower half of the pattern by covering or masking the lower half of the slit, all we succeed in doing is changing the *entire* interference pattern, which still remains symmetrical above and below the center-line on the screen. Attempting to mask the lower half of the slit, in effect, simply *changes* the slit width itself…thereby changing the physical set-up of the experiment.

The inescapable symmetry of the interference pattern seen at the screen suggests some kind of corresponding symmetry may be at work at the slit, too.

Recall that, in the DSI experiment, we can always determine which of the two slits each individual photon passes through…*but, if we do, the interference pattern disappears.* A pre-condition for the DSI interference pattern to appear is that we must be *unable* to distinguish *which* of the two slits the particle has passed through.

Perhaps a similar principle is at work in the single-slit interference experiment, except this time between *pairs* of individual sub-slits *within* the single slit. If the members of each pair of sub-slits are chosen as being symmetrical about the center of the slit, each pair of sub-slits can act like a "component" DSI experiment.

Does this scheme really work? Can we analyze the SSI experiment as an *aggregate* of many of these "component" DSI-type experiments?

The short answer is *yes*. The plan of attack is to show that, for the single-slit interference experiment, the *total* intensity at any point on the screen is the *sum* of the individual intensity contributions of all the component *double*-slit experiments. Each successive component DSI experiment has an increasing sub-slit separation distance, so that the entire series of component DSI experiments spans the entire range of sub-slit separations from 0 to the complete slit width, W.

Each component DSI experiment will contribute a different amount to the intensity at the point, P_Y, on the screen, and the *sum* of all these individual contributions will be the measured intensity at point P_Y in the SSI experiment.

In mathematical terms, it's possible to show that:

(Eq. 9.3) $$\sum_{S=0}^{S=W} I_{DSI} = I_{SSI}$$

where S is each *component* DSI sub-slit *separation*, W is the single-slit's total width, I_{DSI} is the *component* DSI intensity contribution, $\Sigma\, I_{DSI}$ is the *sum* of all these contributions, and I_{SSI} is the single-slit intensity at a point, P_Y, on the screen.

To avoid slowing down the narrative, the complete mathematical derivation of this conclusion is left to Appendix B.

The point of this very short chapter has been to demonstrate that the *single-slit* experiment can be represented as the aggregate of many component *double-slit* experiments. Since DSI experiments can be explained by the "toy" DMI model (as we saw in Chapter 8), then the particle-based DMI model can *also* explain the SSI experimental results.

The DMI “toy” model of both the SSI and DSI experiments has the following features:

1. Although particle-based, it can account for the observed, statistical build-up of the “wave-like” interference patterns in both the DSI and SSI experiments.

2. It applies not only to *beams* composed of many particles, but to *individual* particles, as well.

3. It sidesteps the question of wave/particle duality, as the model is solely based on particles.

4. Considerations of the enigmatic QM wave-function—and its equally mysterious ‘collapse’—are not really required in the “toy” DMI model.

5. The fact that alterations in the experimental setup (changing the slit width, for example, in the SSI experiment, or the opening or closing of one slit in the DSI experiment) can affect the observed pattern is shown to be a consequence of both the presence and positions of the allowed DMI trajectories’ endpoints on the screen. These trajectories are, of course, *non-physical*; they are strictly *geometrical* in nature. As such, it’s no surprise they can exhibit ‘non-local’ behavior.

But there’s a cost associated with all these advantages: the “toy” DMI model *discards* the assumption of *continuous* particle motion…and that’s a pretty dramatic step to take, indeed.

CHAPTER 10

PHOTON POLARIZATION AND THE EPR EXPERIMENT

Back in Chapter 5, we talked about quantum entanglement, Bell's Inequality, and a version of the EPR experiment actually performed by Prof. Alain Aspect at the University of Paris. We saw how Aspect's experiment, which measured entangled photon polarizations, *violated* Bell's Inequality, conclusively proving that, at the quantum scale, 'reality' must be—at the very least—somehow *non-local*.

Although experimentally confirmed, EPR 'non-locality' is remarkably *private*; the 'non-local' connection exists *only* between the two members of the entangled photon pairs. That means it is completely inaccessible to us as a means of communication.

In this chapter, we're going to look closely at Aspect's version of the EPR experiment, and see if we can't gain some insight into the nature of this mysterious quantum 'non-locality'.

Description of the Experiment:

A source of randomly polarized, entangled photon pairs is located mid-way between two polarizers (labelled A and B). Beyond each polarizer a photon detector registers whether the photon has passed through the polarizer. See Figure 10.1.

FIG. 10.1 The EPR Experiment with Polarizers.

One polarizer is fixed, arbitrarily, at 0 degrees, to serve as a reference. The other polarizer can be freely rotated about the axis of transmission of the photons to any angle, θ, relative to 0 degrees.

As each pair of entangled photons is generated (each “event”), the two photons travel in opposite directions along the axis of propagation, and each photon will encounter a polarizer. If the photon passes its respective polarizer, a “1” is registered at the associated detector; if it fails to pass, a “0” will be registered. For each event, the outcomes at both detectors are recorded together as a set.

There are only four possible outcomes for each event: {0,0}…{0,1}…{1,0}…{1,1}. In this notation, for example, an outcome of {0,1} means *no* photon was registered at detector A, but a photon *was* registered at detector B. The notation {1,1} means a photon was registered at *both* detectors A and B…and so forth.

Results of the EPR Experiment:

When considered *independently*, the probability a randomly polarized photon will pass a polarizer at any angle is ½. If we look *only* at the results for polarizer A, for example, about half the photons will pass and register at the detector, and about half will fail to pass. (We can call this the “50% Rule”).

When the two polarizers are aligned (at, say, $\theta = 0°$), the outcomes at polarizers A and B will *always* be the same…that is, the results will always be either {0,0} or {1,1}. In this case, the outcomes are *perfectly* correlated, so let's call this the "0 Degree Rule".

When the polarizers are rotated at 90 degrees to one another ($\theta = 90°$), the results at polarizers A and B will always be the *opposite* of one another…that is, the outcome will always be either {0,1} or {1,0}. The results are perfectly *anti*-correlated, and we can call this the "90 Degree Rule".

How about angles *between* 0 and 90 degrees? We said back in Chapter 5 that QM provides a simple rule for this situation; for convenience, it is repeated here:

(Eq. 10.1) $$P_{\{\mathrm{CORR\ A,B}\}} = \cos^2 \theta$$

where $P_{\{\mathrm{CORR\ A,B}\}}$ is the *probability* the outcomes at polarizers A and B are correlated, and θ is the rotation angle *between* the two polarizers. Knowing this, the probability the outcomes at A and B are *anti*-correlated is easily determined:

(Eq. 10.2) $$P_{\{\mathrm{ANTI\text{-}CORR\ A,B}\}} = 1 - \cos^2 \theta \text{ or } P_{\{\mathrm{ANTI\text{-}CORR\ A,B}\}} = \sin^2 \theta$$

Since the probability the outcomes are correlated must be the *sum* of the probabilities for outcomes {0,0} and {1,1}, and both these outcomes are *equally* likely, the probabilities for all four possible outcomes can be derived:

(Eq. 10.3a) $$P\{0,0\} = \frac{\cos^2 \theta}{2}$$ (Eq. 10.3b) $$P\{1,1\} = \frac{\cos^2 \theta}{2}$$

(Eq. 10.3c) $$P\{0,1) = \frac{\sin^2 \theta}{2}$$ (Eq. 10.3d) $$P\{1,0\} = \frac{\sin^2 \theta}{2}$$

Equations 10.3a through 10.3d are in agreement with both the QM predictions and the actually observed experimental results…and are somehow *non-local* because Equation 10.3d can be made to *violate* one form of Bell's Inequality.

Once again, let's consider Aspect's experiment at polarizer angles of $\theta = 0$, 22.5, and 45 degrees.

Using Equation 10.3d, we get the following probabilities:

$P\{1,0,X\} = \frac{\sin^2(22.5°)}{2}$ (Polarizer A = 0°, Polarizer B = 22.5°)

$P\{X,1,0\} = \frac{\sin^2(22.5°)}{2}$ (Polarizer A = 22.5°, Polarizer B = 45°)

and,

$P\{1,X,0\} = \frac{\sin^2(45°)}{2}$ (Polarizer A = 0°, Polarizer B = 45°)

As shown back in Chapter 5, Bell's Inequality states:

$P\{1,0,X\} + P\{X,1,0\} \geq P\{1,X,0\}$.

Plugging in the actual values for the polarizer settings at 0, 22.5 and 45 degrees gives:

$$\frac{\sin^2(22.5°)}{2} + \frac{\sin^2(22.5°)}{2} \geq \frac{\sin^2(45°)}{2}$$

So, $\frac{(.14645)}{2} + \frac{(.14645)}{2} \geq \frac{.5}{2}$; $(.14645) \geq .25$

As we saw in Chapter 5, this final inequality is *not* true…and we're faced with a clear *violation* of Bell's Inequality. A local, ‘hidden-variable’ type model of photon polarization—the kind favored by Einstein—*simply doesn’t work.*

Immediately, though, this raises the question: what mechanism *can* account for the perfect correlation seen when θ = 0 degrees, or the perfect *anti*-correlation when θ = 90 degrees?

Ruling out a local, ‘hidden-variable’ model seems to force us to acknowledge some form of *non-local* interaction between the members of each entangled photon pair.

A possible clue as to how to proceed comes from Equation 10.3b, which gives the probability for an outcome of {1,1} in the EPR experiment.

Equation 10.3b is familiar to physicists as the “Malus Law” of polarization, mentioned in Chapter 5, and it pre-dates QM by more than a century.

A slight re-arrangement of Aspect’s version of the EPR experiment gives the “classical” Malus experiment, shown in Figure 10.2.

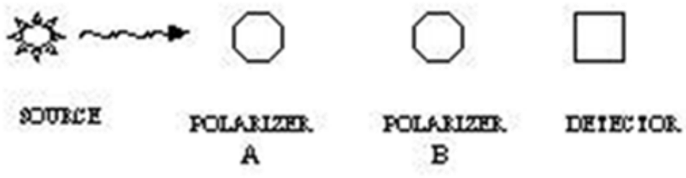

FIG. 10.2 The Malus Experiment.

Whereas Aspect’s EPR experiment lets us distinguish between *four* possible outcomes, the Malus experiment can only distinguish between *two*: {1,1} or {X,0}. That is, unless *both* polarizers permit a photon to pass, *no* photon will be detected passing through the second polarizer, B. (The term {X,0} is really just the sum of the outcomes {0,0} and {1,0}).

Since the probabilities of the four possible outcomes are so closely inter-related, knowing any *one* of the probabilities automatically determines the other three.

A Geometrical Model of the Malus Law:

The “Malus Law” of polarization arises very naturally in the “classical” electromagnetic wave model of light; it is a consequence of the vector projections of the various electric and magnetic fields involved. But how might the “Malus Law” apply to *individual*, particle-like photons?

Consider the following, very simplistic “toy” model of polarization:

1. Arbitrarily, assume the transmission axis of the photons is along the z-axis. Every polarizer is regarded as separating the x,y plane (that is, the plane perpendicular to the transmission axis) into a number of parallel “channels”, each of width, w. Note that neither the width, w, nor the *number* of channels is given explicitly; we can make w as small as we’d like. See Figure 10.3, below.

2. If two polarizers are in line with one another, there results a geometric “overlap” pattern of the two sets of channels, the configuration of which depends on the relative angle, θ, between the polarizers. See Figure 10.4, below.

3. This geometric “overlap” pattern is composed of a number of identical *area elements*, A_E. Figure 10.5, below, shows a close-up of a single such area element. Each area element is a parallelogram of equal sides, and each *side*, S_E, has a length given by:

(Eq. 10.4) $S_E = (1 / \sin \theta)\ w$

Each area element A_E has an *area* equal to the algebraic vector product of its two equal sides:

(Eq. 10.5) $A_E = (1 / \sin \theta)\ w^2$

As θ approaches 0 degrees, the “channels” of the two polarizers approach perfect alignment, and any photon passing the first polarizer, A, will also pass the second polarizer, B…satisfying the “0 Degree Rule”.

As θ approaches 90 degrees, however, the sides, S_E, of each area element approach 1w, and the area of each area element, A_E, approaches $1w^2$. Although the area element A_E is non-vanishing, *no* photons will pass the second polarizer, B, in accordance with the “90 Degree Rule”.

As we begin to *decrease* θ from 90 degrees, photons *do* begin to pass through polarizer B, and a second, smaller *sub-area* becomes apparent (see Figure 10.6, below). This sub-area, A_F, is contained *within* the area element A_E, and is also a parallelogram. The sides of the sub-area A_F are equal, and are *always* equal to 1w. The area of A_F is given by:

(Eq. 10.6) $A_F = \sin \theta\ w^2$

As the angle, θ, *decreases* from 90 degrees, the sub-area, A_F, decreases towards 0.

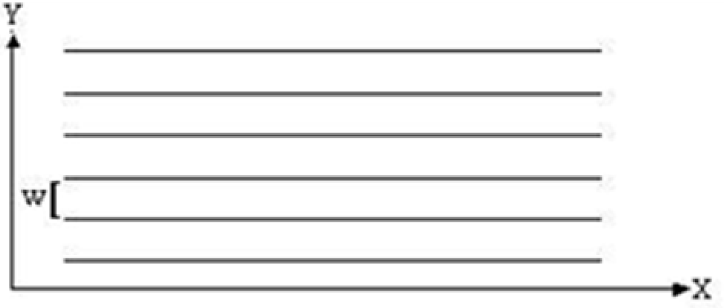

FIG. 10.3 Simple Geometrical Model of a Polarizer

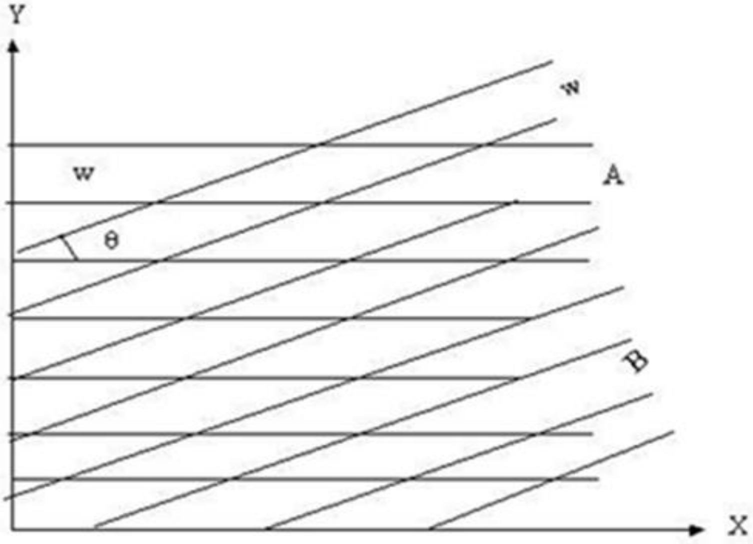

FIG. 10.4 Overlap Pattern of 2 Polarizers.

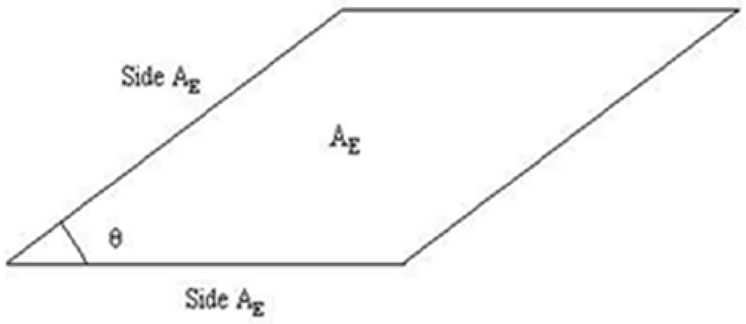

FIG. 10.5 A Single Area Element from Fig. 10.4

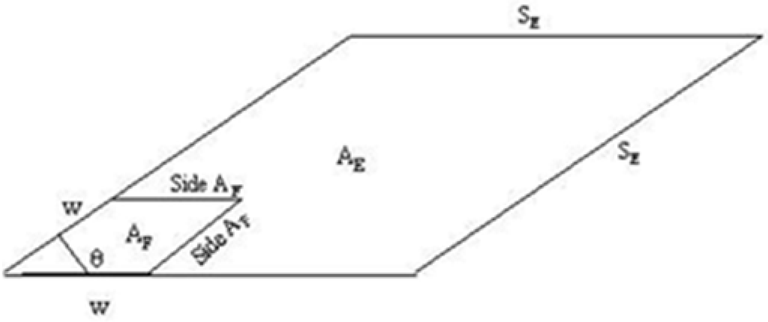

FIG. 10.6 The Sub-Area A_F of the Overlap Area Element, A_E

Our "geometrical" model of the Malus Law is then as follows:

1. One-half of the randomly polarized photons will *pass* the first polarizer, A, in accordance with the "50% Rule". These photons can then be *said* to be polarized at angle A, because they will *always* pass additional polarizers set to angle A.

2. A single such photon, upon arrival at the second polarizer, B, will strike *somewhere* within a single area element, A_E, of the overlap pattern.

3. If the photon strikes within the sub-area A_F, *it will not pass* polarizer B. If the photon strikes *outside* the sub-area A_F, *it will pass* polarizer B.

The probability the photon strikes the area element, A_E *within* the sub-area, A_F, is given by the *ratio* of A_F to A_E:

(Eq. 10.7) $$\frac{A_F}{A_E} = \frac{\sin\theta\, w^2}{(1 / \sin\theta)\, w^2} = \sin^2\theta$$

And, the probability the photon strikes the area element A_E *outside* of the sub-area A_F is given by:

(Eq. 10.8a) $$1 - \frac{A_F}{A_E} = 1 - \sin^2\theta = \cos^2\theta$$

Since only ½ of the randomly polarized photons will pass the first polarizer, A, Equation 10.8a should be *multiplied* by a probability of ½, yielding Equation 10.8b:

(Eq. 10.8b) $$\tfrac{1}{2}\cos^2\theta$$

Equation 10.8b is identical to the “Malus Law” of polarization, but derived here from a simple, “toy” geometrical model, one applicable to *individual* photons.

A Geometric Model of Aspect’s EPR Experiment:

A final point must be noted before this “toy” geometrical model of polarization can be applied to Aspect’s version of the EPR experiment. In Aspect’s experiment, it is extremely *unlikely* the two polarizers (A and B) will be *exactly* equidistant from the entangled photon source; for each emission of an entangled photon pair, one of the entangled photons will interact with its respective polarizer *first*, so long as there is even the *slightest* difference in the distances to the source.

Arbitrarily, we label this closer polarizer as “polarizer A”, and the outcome at polarizer A is then, by definition, always determined *first*...even if only for an infinitesimal amount of time.

(Readers familiar with relativity theory may have some concerns here, regarding ‘frames of reference’. An observer *moving* with respect to polarizers A and B might observe the result at detector B *first*, before knowing the outcome at detector A. But, because detectors A and B are *stationary* with respect to one another, the *geometrical* “overlap” pattern between polarizers A and B is *already* established; a moving observer may simply become *aware* of the outcomes at polarizers A and B at times different from observers *stationary* with respect to polarizers A and B).

Consequently, we know *something* about the photon headed towards polarizer B, even *before* it interacts with polarizer B. Based on the outcome at polarizer A, we know whether the entangled partner photon headed towards polarizer B is polarized at either A° *or* at (A+90)°. For example, suppose photon A *passes* through polarizer A, arbitrarily set at A degrees. It’s entangled partner—photon B—will *pass* polarizer B (if this polarizer is also set to A degrees), or *fail* to pass polarizer B, if polarizer B is set to (A+90) degrees. The converse of this is also true…if a photon *fails* to pass a polarizer set to A°, it’s entangled partner *will* pass a polarizer set to (A+90)°.

If the photon *passed* at polarizer A, the geometrical “overlap” pattern at Polarizer B is shown in Figure 10.7; if the photon *failed* to pass at polarizer A, the equivalent geometrical overlap pattern at Polarizer B is as shown in Figure 10.8.

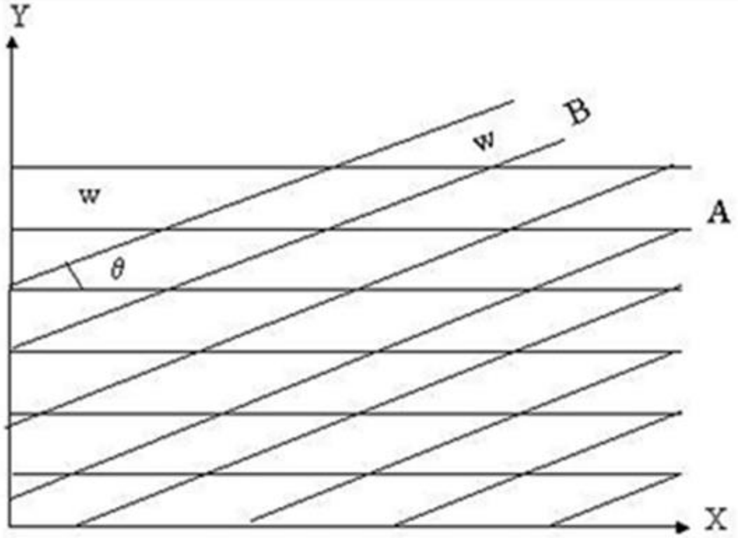

FIG. 10.7 The Overlap Pattern at Polarizer B if Photon A Passes Polarizer A.

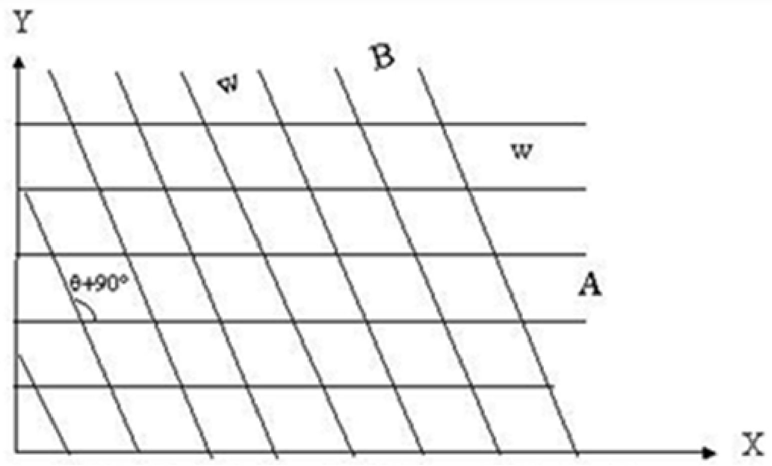

FIG. 10.8 The Overlap Pattern at Polarizer B if Photon A Fails at Polarizer A

The outcome of each ‘event’ is determined by just two considerations:

1. The probability a photon of random, unknown polarization passes at polarizer A (this probability is equal to ½, from the “50% Rule”).

2. The subsequent, local, *random* interaction of photon A’s entangled partner (photon B) with the appropriate “overlap” pattern at polarizer B.

Note that the geometrical “overlap pattern” to be used at polarizer B is *determined* by the outcome at polarizer A. Since both entangled photons are identical, and the result at polarizer A is determined *first*, the photon en route to polarizer B is known to be polarized at either A° or at (A+90) °…*even before it actually interacts with polarizer B.*

The ‘non-local’, EPR-type correlations produced by this “toy” geometric “overlap” model are in complete agreement with both the QM predicted and experimentally observed results…but are in no way dependent on any ‘non-local’ influences *between* the entangled photons. Instead, the correlations occur as a result of the geometrical “overlap” pattern arising between the polarizers *themselves.*

Since these correlations *violate* Bell’s Inequality, they must be ‘non-local’, but this non-locality is seen to be *geometrical* in nature, arising from the simple restrictions imposed by the “toy” geometrical “overlap” model of polarization.

Furthermore, these correlations can *only* exist between two polarizers at a time.

Introduction of a *third* polarizer *between* an initial pair of two polarizers alters the “end-to-end” geometrical “overlap” pattern…a consideration which accounts for the “3-Polarizer Paradox” discussed in the section on Quantum Logic, back in Chapter 4.

In the “3-Polarizer Paradox”, two polarizers (A and B) are rotated at 90° to each other in a Malus-like experimental configuration. About half of the randomly polarized photons will pass through polarizer A, but *none* of these photons will pass through polarizer B, in accordance with the “90° Rule”.

However, if a *third* polarizer (labelled ‘C’)—offset by 45° to *both* polarizers A and B—is inserted *between* polarizers A and B, some photons *will* now pass through polarizer B. See Figure 10.9.

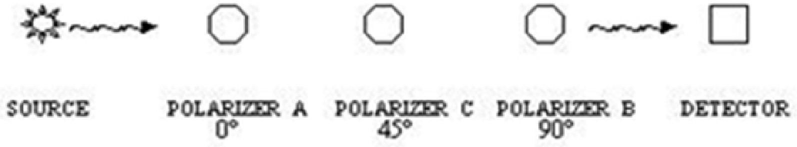

FIG. 10.9 The "3 Polarizer Paradox"

The "end-to-end" probability a randomly polarized photon will pass through all *three* polarizers, $P_{\{AB\}}$, is the *product* of the two separate "Malus Law" probabilities, $P_{\{AC\}}$ and $P_{\{CB\}}$:

(Eq. 10.9) $$P_{\{AB)} = P_{\{AC\}} \text{ x } P_{\{CB\}}$$

Substituting the actual values for the probabilities,

$$P_{\{AC\}} = \tfrac{1}{2} \cos^2 (45^\circ), \text{ and } P_{(CB\}} = \tfrac{1}{2} \cos^2 (45^\circ)$$

From Equation 10.9, we get:

(Eq. 10.10) $$P_{\{AB\}} = (.25) \text{ x } (.25); \quad \text{so} \quad P_{\{AB\}} = .0625$$

Even though polarizers A and B are still rotated at 90° to one another, introduction of the *third* polarizer—polarizer C—invalidates the "90° Rule" between polarizers A and B…and there is now a non-zero probability a photon can pass through all *three* polarizers.

If our "geometric" model of the Malus Law only applies between two polarizers, how is the outcome at the first encountered polarizer, A, determined?

To state the trivially obvious, *any* photon approaching polarizer A will either pass or fail at polarizer A. This means we can say *any* photon approaching polarizer A is *either* polarized at A° (if it passes through) *or* at (A+90)°, if it fails to pass through. In EPR-type polarization experiments, this statement must also apply to the entangled partner photon, *even before it interacts with polarizer B.*

In conclusion, the “toy” geometric model of polarization described above not only agrees with the QM predicted, ‘non-local’ correlations revealed in Aspect’s version of the EPR experiment, it also accounts for both the “Malus Law” of polarization and the “3-Polarizer Paradox”. And it applies to *individual* photons, as well.

CHAPTER 11

PARTICLE SPIN AND THE EPR EXPERIMENT

In the last chapter, we considered a version of the EPR experiment that used photons, and their polarizations, to see how the ‘non-local’ correlations could be explained by a “toy” geometrical model. Einstein’s infamous “*spooky action at a distance*”, although undeniably real, was shown to be a result of the *geometrical* relationship between the polarizers—requiring no *physical* influences between the entangled particles.

But what about particles *other* than photons? In this chapter, we’ll look at a variation of the EPR experiment that uses entangled electrons, and a dynamic attribute referred to as “spin direction”.

Spin is a peculiarly quantum mechanical attribute, one that has no real counterpart in our everyday world. Historically, the idea of electron spin was first introduced to account for some anomalous features found in the spectrum of the hydrogen atom. Originally, electron spin was naively thought to represent an actual, physical rotation of the electron, the idea being that a charged particle—like the electron—would have an intrinsic magnetic field if it rotated about its central axis…much like a child’s toy top. Such a spinning, charged particle would be accompanied by a magnetic field, and the interaction of this *intrinsic* magnetic field with an *externally* applied magnetic field could be used to account for subtle changes in the particle’s energy…just matching the anomalies observed in the hydrogen spectrum.

It was soon realized that this model of an electron as a spinning, electrically charged sphere couldn’t really be valid, because the electron, so far as experiment can determine, is a *point* particle, with *no* measurable diameter. Nevertheless, the electron *does* have an intrinsic magnetic field, as first demonstrated by the German physicists Otto Stern and Walther Gerlach in 1922.

Stern and Gerlach developed a simple device called—appropriately enough—a *spin analyzer*, as shown in Figure 11.1. A charged particle passing through this apparatus encounters an *inhomogeneous* magnetic field, and is deflected towards either the north or south magnetic pole of the device. By convention, if the particle is deflected towards the north magnetic pole, its spin is arbitrarily defined as being ‘up’; if deflected towards the south magnetic pole, the spin is defined as being ‘down’. All spin analyzers, then, have *two* outputs: a spin ‘up’ output, and a spin ‘down’ output. Any incoming particle emerges from *either* the ‘up’ *or* the ‘down’ output.

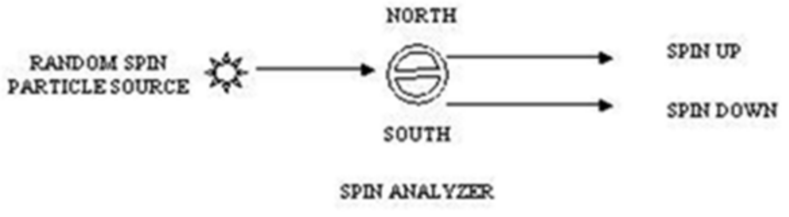

FIG. 11.1 Details of a Stern-Gerlach Spin Analyzer.

Description of the Experiment:

For this version of the EPR experiment, a source of random spin, entangled electron pairs is located midway between two Stern-Gerlach spin analyzers (see Figure 11.2). For each emission of an entangled electron pair, the spin direction of each particle pair is random, but the spin directions of each partner are always *anti*-correlated (that is, if one electron in the pair happens to have a spin of ‘up’, its entangled partner always has a spin of ‘down’, and vice-versa).

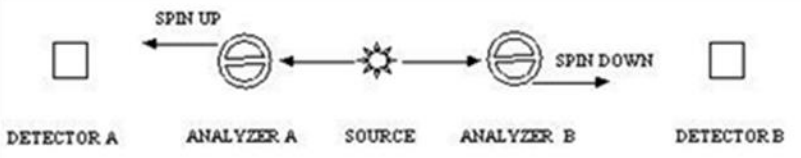

FIG. 11.2 The EPR Experiment with Spin Analyzers.

The spin analyzers are free to rotate about the axis of propagation of the particles, but, for reference purposes, one of the analyzers is fixed at 0 degrees.

This electron spin version of the EPR experiment has many similarities to the EPR experiment using photon polarizations, but there are some important differences. In the photon-based version, every photon either passes or fails to pass through its associated polarizer. In the electron spin EPR experiment, every electron *always* passes through its associated spin analyzer, but now the “pass/no pass” result for photons is replaced by a “spin up” or “spin down” result.

Also, in Prof. Aspect’s version of the photon polarization EPR experiment, the entangled photons will behave the *same* at identical polarizer angles (if photon A, for example, passes a polarizer at 0^o, its entangled partner—photon B—will *also* pass a polarizer at 0^o). Entangled electrons have *opposite* spins. If, say, electron A passes a spin analyzer set at 0^o with “spin up”, its entangled partner electron—electron B—will pass a spin analyzer set at 0^o with “spin down”.

Results of the Experiment:

Considered *independently*, the probability a particle with a random spin direction will pass a spin analyzer with spin ‘up’ is ½, and the probability it will pass with spin ‘down’ is also ½ (we can call this the “50% Rule”).

When the rotation angle, θ, *between* the two spin analyzers is 0 degrees, the outcomes at the two spin analyzers will always be perfectly *anti*-correlated (the “0° Rule”).

When the rotation angle, θ, between the two spin analyzers is 90°, the correlation between the outcomes is completely *random* (the “90° Rule”), and when the rotation angle, θ, is 180°, the outcomes are perfectly correlated (the “180° Rule”).

In general, QM tells us the rule for calculating the probability the outcomes are correlated for *any* rotation angle, θ, between the two spin analyzers:

(Eq. 11.1) $$P_{\{\text{CORR A,B}\}} = \sin^2(\theta/2)$$

where $P_{\{\text{CORR A,B}\}}$ is the probability the outcomes at spin analyzers A and B are correlated (i.e., *both* are spin ‘up’ or *both* are spin ‘down’).

Let’s once again compare the photon polarization version of the EPR experiment with the electron spin version of the EPR experiment. Equation 11.1, above, looks *somewhat* like Equation 10.2 (the probability the entangled photons will have *anti*-correlated polarizations). Since entangled electrons have *opposite* spins, and entangled photons have *identical* polarizations, the sine term in Equation 11.1 makes sense. What’s really different, though, is the term (θ/2), as opposed to the term, θ, in Equation 10.2.

To develop a “toy” *geometrical* model of the spin analyzer correlations, we’ll follow an approach similar to the one used for the photon polarization version of the EPR experiment, as detailed in Chapter 10.

A Geometric Model of the Malus Experiment with Spin Analyzers:

First, a simple re-arrangement of the EPR experiment gives us a spin analyzer “analog” of the Malus experiment. Here, each electron passes successively through *two* Stern-Gerlach spin analyzers, one after the other. For simplicity, let’s arbitrarily place the second spin analyzer (Analyzer B) in the spin ‘up’ output of the first spin analyzer (Analyzer A), as shown in Figure 11.3.

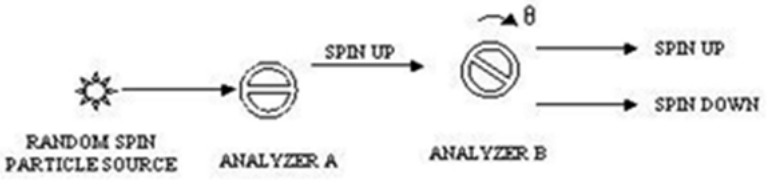

FIG. 11.3 Spin Analog of the Malus Experiment.

Assuming the electrons travel along the z-axis, we regard each spin analyzer as dividing the x,y plane into a number of, parallel “channels”, each of equal width, w. As before, both the *number* of channels and the *width* of each channel is left unspecified; we can make w as small as we’d like.

Just as in the “toy” geometric polarizer model presented in Chapter 10, when the two spin analyzers are in line with another, the two sets of channels will produce an geometrical “overlap” pattern, the configuration of which depends on the rotation angle, θ, between the two spin analyzers. Refer back to Figures 10.3 to 10.5 for illustration.

The “overlap” pattern, once again, is composed of a large number of individual area elements. Each of these elements has an area, $A_E = (1 / \sin\theta)\, w^2$.

Unlike in the “geometric” model of photon polarizers, this time each area element, A_E, is divided into *three* sub-areas: two *equal* triangular areas, A_T, and one interior rectangular area, A_R. See Figure 11.4.

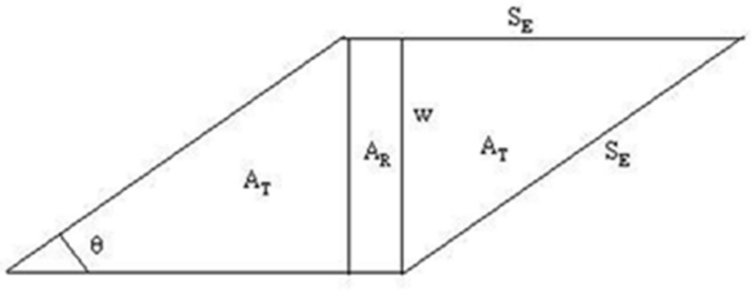

FIG. 11.4 The Sub-Areas A_T and A_R of the Overlap Area Element A_E

The area of the rectangular sub-area, A_R is:

(Eq. 11.2)
$$A_R = \frac{1 - \cos\theta}{\sin\theta}\, w^2$$

And the area of *each* of the triangular sub-areas, A_T, is:

(Eq. 11.3)
$$A_T = \frac{1}{2}\,\frac{\cos\theta}{\sin\theta}\, w^2$$

Any incoming particle must strike *within* a single area element, A_{E}. Furthermore, the incoming particle must strike the area element *either* within one of the two equally-sized triangular sub-areas, *or* within the rectangular sub-area, A_{R}.

When θ = 90°, the triangular sub-areas *vanish* completely, and the *entire* area element A_{E} is composed of the rectangular sub-area, A_{R}. Half of the particles striking within this sub-area will emerge from the spin analyzer with spin 'up'; the other half will emerge with spin 'down'.

In other words, particles striking within the sub-area A_{R} will emerge from the spin analyzer with a *random* spin direction of 'up' or 'down', in accordance with the "90° Rule".

For *any* angle θ between the spin analyzers the probability, $P_{\{AR\}}$, the particle will strike the area element A_{E} *within* the sub-area A_{R} is given by the *ratio* of the areas, A_{R} to A_{E}:

(Eq. 11.4) $$P_{\{AR\}} = (A_{R} / A_{E}) = 1 - \cos\theta$$

Half of the particles striking within the sub-area A_{R} will change spin direction, so the probability the incoming particle's spin is changed, or "flipped", is:

(Eq. 11.5) $$P_{\{ANTI\text{-}CORR\}} = \tfrac{1}{2}(1 - \cos\theta)$$

where $P_{\{ANTI\text{-}CORR\}}$ is the probability the outcomes at the two spin analyzers are *anti*-correlated—that is, if the particle emerges from the first spin analyzer with spin 'up', it will emerge from the second analyzer with spin 'down'—and vice-versa.

By trigonometric substitution, Equation 11.5 can be re-written as:

(Eq. 11.6) $$P_{\{ANTI\text{-}CORR\}} = \sin^2(\theta/2)$$

From this, we can obtain the *correlation* probability—that is, the probability a particle's spin remains *unchanged* after passing through the second spin analyzer:

(Eq. 11.7) $$P_{\{CORR\}} = 1 - \sin^2(\theta/2) = \cos^2(\theta/2)$$

To summarize, our "toy" geometric model of two spin analyzers arranged in a Malus-like configuration works like this:

1. Spin analyzers A and B produce a geometric "overlap" pattern similar to that seen in the "toy" geometric model of polarizers, as detailed in Chapter 10. Again, this "overlap" pattern is composed of a number of identical area elements, A_E. Any particles arriving at the second spin analyzer (analyzer B) must strike within one of these area elements.

2. At analyzer B, if the particle strikes an area element, A_E, *within* the rectangular sub-area, A_R, there is a 50% chance it will emerge from analyzer B with its spin "*flipped*", and a 50% chance it emerges from analyzer B with its spin *unchanged*.

3. Or, if the particle strikes an area element, A_E, *within* either of the two *triangular* sub-areas, A_T, it emerges with its spin unchanged.

A Geometric Model of the EPR Experiment with Spin Analyzers:

Before we can apply this model to an EPR-like configuration of spin analyzers, two conditions must be noted.

First, as was the case with the polarizer version of the EPR experiment, it is *very* unlikely that the two spin analyzers in the EPR experiment will be *exactly* the same distance from the particle source; therefore, one of the particles in the entangled pair (arbitrarily labeled as particle "A") will interact with its respective spin analyzer *first*...even while its partner is still en route towards spin analyzer B. This means we always know something about particle B's spin direction *before* it interacts with spin analyzer B, even if for only an *infinitesimal* amount of time. If particle A emerges from its spin analyzer with a spin direction of 'up", its entangled partner particle—particle B—must have a spin direction of 'down'…and vice-versa.

Second, the particle spins in each entangled pair are in *opposite* directions. This means the correlations derived for a Malus-type experimental arrangement, as derived above, must be *reversed* for the EPR arrangement. Accordingly, equations 11.6 and 11.7 become:

(Eq. 11.8) $$P_{\{\text{ANTI-CORR}\}} = \cos^2(\theta/2)$$

And,

(Eq. 11.9) $$P_{\{\text{CORR}\}} = \sin^2(\theta/2)$$

Equation 11.9 is identical to the QM predicted—and experimentally observed—EPR correlations for the spin directions, as given in Equation 11.1.

The complete, "toy" geometric spin analyzer model for the EPR experiment is then as follows:

1. First, a particle with a random, unknown spin direction—particle A—interacts with spin analyzer A, and emerges, with equal probability, with a spin direction of either spin ‘up’ or spin ‘down’. For this example, assume particle A emerges from spin analyzer A with a spin direction of ‘up’.

2. Particle A’s entangled partner—particle B—is then known to have a spin direction of ‘down’, even *before* it interacts with *its* associated spin analyzer (analyzer B).

3. The outcome at spin analyzer B is locally determined by the following considerations:

Particle B will randomly strike one of the area elements, A_E, contained in the “overlap” pattern. If particle B strikes within the rectangular sub-area, A_R, of the area element, there is a 50% chance it will emerge from analyzer B with its spin direction *unchanged* (in this example, that will be spin ‘down’), and a 50% chance it will emerge with its spin “*flipped*” (that is, spin ‘up’).

If, instead, particle B happens to strike the area element, A_E, within *either* of the two triangular sub-areas, A_T, it will emerge with its spin direction unchanged (for this example that will be spin ‘down’).

This “toy” geometric model of the spin analyzer EPR experiment yields results in perfect agreement with both the QM predicted and experimentally observed results. As was the case with the polarizer version of the EPR experiment, the ‘non-locality’ evident in the experimental results is seen to be a consequence of the geometric relations between the spin analyzers *themselves*, as determined by the “overlap” pattern.

No instantaneous interaction between the entangled partners is required, and no appeals to “hidden variable” type models are needed, to account for the observed, ‘non-local’, correlations.

CHAPTER 12

CAN THE DRAGON BE TAMED?
FINAL THOUGHTS REGARDING PART 2

“If it ain’t broke, don’t fix it.”

— 20th Century American proverb

So, where does all this leave us?

Throughout this book, it has been repeatedly stressed that QM is a *supremely* successful theory, one that—to date—has passed *every* experimental test to which it has ever been put.

But, because of its very abstract mathematical structure, QM has little or nothing to say about the underlying *nature* of physical ‘reality’…despite being so good at predicting the outcomes of experiments designed to *test* that reality. Proof of this comes from the multitude of interpretations available for QM, many of which were developed by the founders of the theory itself.

In Part 1, we looked at two “showpiece” quantum experiments, and talked about the “quantum weirdness” associated with each.

The DSI and EPR experiments demonstrate the surprising—yet undeniable—*strangeness* of the physical world, and QM theory correctly predicts the outcomes of them both. But QM theory *itself* remains open to interpretation, and these interpretations are, in themselves, pretty outrageous.

Should we choose to believe there is *no* underlying ‘quantum reality’, as the Copenhagen Interpretation would have it? Or that we *create* the underlying reality by choosing which experiment to perform (as in the “observer” or “*consciousness* created” reality interpretations)? How about accepting multiple universes, or non-Boolean logic, or Heisenberg's weird duplex reality? *All* of these interpretations are compatible with QM theory, but all require we adopt some *very* peculiar ideas.

We've seen how Heisenberg's Uncertainty Principle prohibits us from ever *experimentally* answering our question as to *what goes through the slits,* and how the "Schrödinger's Cat" thought experiment implies that QM's working answer to that question—the wave-function—may not really be an answer at all.

Again, QM has passed—with flying colors—*every* experimental test to which it's ever been put. But the theory itself, by its very nature, has almost nothing to say about *why* it is so successful…and this leaves room for some of the strange interpretations mentioned above. QM *permits* such outrageous interpretations, but it does not necessarily *demand* them.

* * *

In Part 2 of this book, "toy" *geometric* models of the DSI and EPR experiments were proposed…models that agree with both the QM predicted and experimentally observed results.

For the DSI experiment, a concrete, *physical* interpretation of the de Broglie wavelength was introduced, based on the idea of *discrete* motion (see Chapter 8). By restricting quantum 'entity' trajectories to *integer* multiples of the de Broglie wavelength, the wave-like behavior seen in the DSI experiments can be successfully accounted for…even when dealing with just a *single* photon or particle at a time. This "discrete motion interpretation" (DMI) model can also be successfully extended to the *single*-slit interference experiment (see Chapter 9).

Some future tests of the DMI model might include applications to a model of the electron in the hydrogen atom, "quantum tunneling" phenomena, and the "electron in a box" problem.

Since the DMI model is *entirely* particle-based, it eliminates any concerns about wave/particle duality or the ‘collapse’ of the wave-function. And, it seems to answer our question: *what goes through the slits*?

* * *

For both the photon polarization and particle spin EPR experiments, introduction of the “toy” geometric “overlap” models lets us account for the QM predicted—and experimentally confirmed—‘non-local’ correlations between entangled quantum ‘entities’…*without* invoking a need for hidden variable models or *physical* influences between the ‘entities’ themselves.

Einstein’s infamous “*spooky action at a distance*” —as revealed through experimental violations of Bell’s Inequality—can be modelled as a consequence of *geometrical* relations *between* the measurement instruments (that is, the polarizers or spin-analyzers) *themselves*.

Recall that in the EPR “toy” geometric models, the “channel” width, w, was intentionally left unspecified…and could be made as small as we’d like. Intuitively, we might expect w needs to be *very* small…perhaps on the order of 1 de Broglie wavelength or so, or perhaps vanishing towards zero.

A surprising feature of these “toy” geometric models is that the channel width, w, can actually be made quite large. Because it is the *ratios* of the various sub-areas to the area element, A_E, that is important—and not the absolute sizes of the areas—w can be on the order of the size of the *entire* polarizer or spin analyzer…and the resultant probabilities will *still* approximate the observed results.

How much stock *should* we place in the “toy” geometric “overlap” models of the two versions of the EPR experiment presented here? Well, mathematically speaking, area is just a measure of the number of ‘points’ contained within a boundary.

The “sub-areas” used in these geometric models need not *necessarily* be in the configurations shown in the figures. But the fact that such simple diagrams can be used to predict the observed EPR correlations *does* suggest a certain validity to this approach.

* * *

The various ideas and “toy” models presented in Part 2 of this book are by *no means* intended as substitutes for, or improvements on, the quantum theory itself...nor should they even be regarded as new interpretations of QM. Instead, they are offered simply as possible models for *visualizing* the underlying physical ‘reality’ of the quantum experiments considered.

Why bother to introduce such “toy” models? Although admittedly unusual in themselves, when compared to the interpretations listed in Chapter 4, they do seem to embody a certain “*economy of weirdness*”…that is, they provide physical models of the strange phenomena revealed by the DSI and EPR quantum experiments… without resorting to such things as multiple-universes, quantum logics, or backwards time-travel.

As shown in the previous discussions, both the DSI and EPR experiments can be described using *geometrical* approaches, and—in many ways—this is most like the de Broglie-Bohm “quantum potential field” interpretation. Here, though, spatial relationships—that is, *geometries*—are used in place of the quantum potential field. Geometry shares many of the characteristics of the de Broglie-Bohm ‘quantum potential field’: it too is ‘non-local’, its strength does not change with distance, and it applies *exclusively* to the pairs of measuring devices involved.

* * *

I sincerely hope you've enjoyed reading this book as much as I've enjoyed writing it…and I welcome any and all criticisms, comments, questions, or concerns.

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APPENDIX A

THE "QUANTUM ERASER" EXPERIMENT

To fully appreciate the following experiment, a working familiarity with the concepts of both wave/particle duality *and* photon polarization is needed—which is why the description of it has been saved until this Appendix.

The "Quantum Eraser" experiment illustrates a wrap-up of several forms of "quantum weirdness": it combines both wave/particle duality *and* photon polarization in a dramatic new way. The concept of the "quantum eraser" was first proposed by the American physicist M.O. Scully and his colleagues, in 1982, but the original version of the actual experiment was rather complex; the simplified version presented here comes from a 2007 Scientific American™ magazine article by R. Hillmer and P. Kwiat.

Description of the Experiment:

We begin with the standard DSI experimental setup (refer back to Chapter 1, and Figure 1.1). Again, a standard laser pointer can be used as the illumination source…and this time there's no need to attenuate the laser beam. As usual, when *both* slits are opened, we see the double-slit interference pattern on the screen.

Next, this basic DSI experiment is *modified* by placing a single polarizer over each slit…we can call these the *slit polarizers*. (See Figure A.1). For this first stage of the experiment, the "screen polarizer" (shown in dotted lines) is removed.

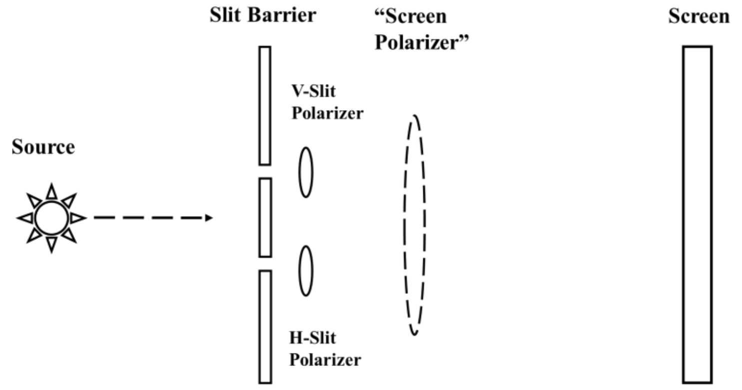

FIG. A.1 The “Quantum Eraser” Experiment

What will be seen on the screen? That depends on the *orientations* of the slit polarizers. If both slit polarizers have the *same* orientation (for example, if both are horizontal, H-polarizers, or both are vertical, V-polarizers), a double-slit interference pattern will still be observed—although the pattern will be somewhat dimmed by the presence of the slit polarizers.

But, if one of the slit polarizers is *rotated* by 90 degrees, so that one slit is covered by an H-polarizer and the other slit is covered by a V-polarizer, the double-slit interference pattern *disappears*. Instead, *two* separate single-slit “smur” patterns are seen, each centered in front of its associated slit. By orienting the slit polarizers in directions perpendicular to one another, we’ve got a way to uniquely distinguish *which* slit each photon in the original beam has passed through.

Next, yet a *third* polarizer is added to the experiment—one large enough to cover *both* slits. Call this third polarizer the *screen polarizer*. If this screen polarizer is oriented in, say, the H-direction, *only* H-polarized photons can pass through it. That is, only photons passing through the H-oriented slit polarizer can reach the screen…and, since we know *which* slit is covered by the H-slit polarizer, we know any photons reaching the screen *must* have come through the slit covered by the H-slit polarizer. The result: a single-slit "smur" pattern, in front of the slit covered by the H-slit polarizer.

Conversely, if we orient the screen polarizer in the V-direction, *only* photons from the V-slit polarizer can pass through it to reach the screen. Since we know which slit is covered by the V-slit polarizer, we know *which* slit these photons have come from. Again, we see a single-slit "smur" pattern, this time in front of the slit covered by the V-slit polarizer.

It's important to note, however, that even the *possibility* of being able to determine *which* slit the photon came from *eliminates* the double-slit interference pattern…we don't actually *need* the screen polarizer at all to destroy the double-slit interference pattern.

As a final test, keep one slit polarizer oriented in the V-direction, and the other slit polarizer oriented in the H-direction. This time, though, the large screen polarizer—which covers *both* slits—is *rotated* 45 degrees in the diagonal, D-direction. From the earlier discussions of polarization, we know there's a *chance* that an H-polarized photon might pass through the 45 degree screen polarizer, and there's also a *chance* a V-polarized photon might pass through the 45 degree screen polarizer. When the two slit polarizers and the screen polarizer are oriented in this way, what will be seen on the screen now?

The double-slit interference pattern—as if by magic—*re-appears*. By setting the screen polarizer at 45 degrees, we've "erased" the *which-slit* information previously obtained by using the slit polarizers alone.

What can this striking experiment tell us about the various interpretations of QM we looked at back in Chapter 4?

In the unmodified DSI experiment, many of the more ‘orthodox’ interpretations regard each photon as passing—somehow—through *both* slits. As mentioned earlier, the English physicist P.A.M. Dirac (who developed the first *relativistic* version of QM theory, thereby accounting for electron spin and introducing the concept of anti-matter) went so far as to assert that a single photon can *only* interfere with *itself*.

Even if true, in the “Quantum Eraser” experiment, the rules of polarization ensure that any photon passing through the V-slit polarizer must be *blocked* by the H-slit polarizer, and vice-versa. This is confirmed by the presence of the single-slit “smur” patterns on the screen, instead of the double-slit interference pattern.

But, when a large screen polarizer at 45 degrees is *added* to the experiment, the interference pattern re-appears.

In the more conventional interpretations of QM, then, it appears as though the original wave-function of each photon is *collapsed* by using slit-polarizers at perpendicular orientations to one another, but then *restored* by introducing the 45 degree screen polarizer. And this, in turn, implies that each photon—in some sense—“remembers” that it had, *in the past*, encountered a two-slit barrier. Photon “memory” like this introduces a whole new kind of “quantum weirdness”.

What about our speculative, particle-based “discrete motion interpretation” (DMI) model, introduced in Chapter 8? How does this model “fit” with the “Quantum Eraser” experiment?

In the DMI model, photons are *always* regarded as particle-like…and, in the unmodified DSI experiment, each particle-like photon passes through just one slit *or* the other…and *neve*r through both.

When both slits are open, the resulting interference pattern arises as a statistical consequence of the locations of the allowed DMI trajectories at the screen. Each photon, when travelling from the source to the screen, follows—at random—just one of these DMI trajectories, regardless of which slit it happens to pass through…but all of the DMI trajectories—through both slits—are possible choices. For a large sample of photons, bright interference fringes will be observed where the endpoints of the DMI trajectories coincide with, or cluster near, one another at the screen; where these trajectory endpoints are sparse, a dark fringe is seen.

In our previous discussions of polarization—and from actual experiments—we've seen that any randomly polarized photon will *either* pass *or* be blocked by a polarizer oriented at any angle. About half the randomly polarized photons will pass, and about half will be blocked (the "50% rule"). Additionally, the EPR-type experiments show that if a photon *passes* a polarizer oriented at any angle, A°, its "entangled", identical partner will be *blocked* by a polarizer rotated at angle (A+90)°… and vice-versa. From this, we can reasonably say that *every* randomly polarized photon is polarized at *either* A° *or* (A+90)°…even *before* its polarization is actually measured.

Polarizers—whatever their configuration may be—have *no* effect whatsoever on the presence or absence of the allowed DMI *trajectories* from the source to the screen. Polarizers can, however, effectively *block* or *permit* photons following these trajectories, depending on the photons' polarizations. *All* the allowed DMI trajectories still exist; whether a given photon can follow a specific one of these trajectories depends on the polarizer(s) it encounters along that specific trajectory.

In the Quantum Eraser experiment, only three possibilities exist for a given, randomly polarized photon emitted from the source:

1). *Either* the photon is absorbed by the slit barrier itself, and so does not pass through either slit.

2). *Or,* the photon encounters the slit covered by the H-slit polarizer, and has about a 50% chance of passing through, and a 50% chance of being blocked by this polarizer.

3). *Or,* the photon encounters the slit covered by the V-slit polarizer; again, it has about a 50% chance of passing through, and a 50% chance of being blocked by this polarizer.

Only some of the randomly polarized photons emitted by the source will encounter, say, the slit covered by the H-slit polarizer…and only some of *these* photons (those polarized in the H-direction) can pass through this slit, and continue to follow DMI-type trajectories from the source, through the H-slit polarizer, and on to the screen. For these H-polarized photons, the DMI trajectories from the *other* slit (the one covered by the V-slit polarizer) are *blocked*…although—in a geometric sense—these trajectories still exist, photons which *pass* a horizontal polarizer would be *blocked* by a vertical polarizer. The same reasoning applies to the source photons that happen to be polarized in the V-direction.

In a DMI-type model of the "Quantum Eraser" experiment, the presence of the V and H slit polarizers effectively reduces the double-slit experiment to two independent *single-slit* experiments, running side-by-side…so accounting for the two independent single-slit "smur" patterns observed on the screen.

If the 45 degree screen polarizer—which covers both slits—is now introduced, the two independent single-slit "smur" patterns encounter the screen polarizer *before* reaching the screen.

Only photons passing through the H-slit polarizer are present in the H-slit “smur” pattern, and only photons passing the V-slit polarizer are present in the V-slit “smur” pattern.

The “Malus Law” of polarization tells us, however, that there is a probability *some* of the H-polarized photons in the H-slit “smur” pattern will pass through the 45 degree screen polarizer, and *some* of the V-polarized photons in the V-slit “smur” pattern will pass through the 45 degree screen polarizer. *All* the photons which successfully pass the 45 degree screen polarizer can now be regarded as being polarized in the 45 degree, D-direction.

In effect, the screen polarizer *itself* becomes a two-slit source of identically polarized photons, and *none* of the DMI-type trajectories to the screen are blocked. *All* the DMI-type trajectories, from *both* slits, are once again available to any photon which successfully passes the 45 degree screen polarizer.

And, on the screen, the double-slit interference pattern *reappears*.

Once again, we have a situation where two *very* different physical models (the ‘orthodox’ QM wave-function and the “toy” DMI model) produce the *same* experimental results.

APPENDIX B

MATHEMATICAL DERIVATION OF THE SSI EXPERIMENTAL RESULTS

Back in Chapter 8, regarding the DSI experiment, Equation 8.6 gave us the *location* of the bright fringes on the screen. What we need now is a more general expression, one that can tell us the DSI intensity at *any* point P_Y on the screen. The "classical" wave-based model provides us with just such an expression:

(Eq. B.1) $$I_{PY} = I_O \cos^2 (\delta/2)$$

where I_{PY} is the DSI intensity at a point, P_Y, on the screen, I_O is the DSI "baseline" intensity—that is, the intensity of the central, brightest fringe—and δ is the so-called "phase angle" at the point P_Y.

Equation B.1 looks pretty simple, but also a little strange, including, as it does, the unfamiliar variable, δ. The "phase-angle", δ, is just a mathematical convenience, related to the *difference* in the path lengths from the two slits to the point, P_Y, on the screen:

(Eq. B.2) $$\delta = \frac{2\pi}{\lambda} (P_A - P_B) \text{ so, } \frac{\delta}{2} = \frac{\pi}{\lambda} (P_A - P_B)$$

again, δ is the phase-angle, P_A is the path length from one of the slits to point P_Y, P_B is the path length from the *other* slit to point P_Y, and λ is the de Broglie wavelength of the particles.

This can be simplified still farther. In a typical DSI experiment, the slit to screen distance, D, is usually *muc*h larger than the slit separation distance, S, and *very* much larger than the wavelength, λ. When this is the case, we can use something called the "small angle approximation", and an excellent approximation for the term $(P_A - P_B)$ is given by:

(Eq. B.3) $$(P_A - P_B) = \frac{YS}{D}$$

where Y is the distance of point P_Y from the center of the screen.

Substituting Equation B.3 into Equation B.2:

(Eq. B.4) $$\delta = \frac{2\pi YS}{\lambda D} \quad \text{and} \quad \frac{\delta}{2} = \frac{\pi YS}{\lambda D}$$

And, substituting Equation B.4 into Equation B.1 gives :

(Eq. B.5) $$I_{PY} = I_o \cos^2 (\pi YS/\lambda D)$$

That's better. The "classical" wave-model term, δ, is gone; Equation B.5 includes only straight-forward geometrical terms (S, Y, D, and λ). All these terms are simply *distances*.

We can simplify this even more. Since, for any given DSI experiment, the terms Y, D, and λ remain constant (once set, these terms shouldn't change during the experiment), and can be gathered together as follows:

(Eq. B.6) $$K = Y\pi / \lambda D$$

where K is a constant, introduced for convenience in the equations that follow.

We can now re-write Equation B.5, the DSI intensity at point P_Y:

(Eq. B.7) $$I_{PY} = I_o \cos^2 (KS)$$

The DSI *amplitude*, A_{PY}, for any point P_Y on the screen is obtained by taking the square root of the DSI *intensity* at that point, so Equation B.7 becomes:

(Eq. B.8) $A_{PY} = A_o \cos(KS)$

where A_O is the DSI "baseline" amplitude.

All the above steps have really only let us simplify the original, "classical" wave-based equation for the DSI *intensity* at any point, P_Y, on the screen (Equation B.1) into a wave-based equation for the DSI *amplitude* at P_Y (Equation B.8).

Next, we need to look closely at the terms I_O and A_O, as used so far. These are the DSI "baseline" intensity and its square root, the DSI "baseline" amplitude, respectively. Ordinarily, in a DSI experiment, I_O is simply the measured intensity seen at the central, brightest DSI fringe, at location $Y = 0$ on the screen; A_O is the amplitude of this brightest fringe, obtained by taking the square root of I_O.

But we want to use Equation B.8 for the amplitude of the many *component* DSI "sub-experiments" needed to construct the *single-slit interference* amplitude at point P_Y. For our purposes, the term A_o in Equation B.8 can be replaced by:

(Eq. B.9) $A_o{*} = A_o / \#sub_W$

where $A_o{*}$ is the "baseline" amplitude for each of the *component* DSI "sub-experiments", and $\#sub_W$ is the total *number* of sub-slits contained *within* the single-slit width, W.

Substituting Equation B.9 into Equation B.8 gives us the *component* DSI amplitude at point P_Y on the screen, at a *sub-slit separation* of S:

(Eq. B.10) $A_{PY}^* = A_o^* \cos(KS)$

where A_{PY}^* is the *component* DSI amplitude at point P_Y.

Next, we're going to sum up all of the *component* DSI amplitudes, for *sub-slit* separations ranging from $S = 0$ to $S = W$:

(Eq. B.11) $\sum_{S=0}^{S=W} A_{PY}^* = (A_{PY}^*$ at sub-slit separation $S_1 \ldots + A_{PY}^*$ at sub-slit separation $S_2 \ldots\ldots + A_{PY}^*$ at sub-slit separation $S = W)$

Each of the successive *sub-slit* separations, S, can be given in terms of the single sub-slit width, w:

(Eq. B.12) $S = w\,(\#sub_S)$

where $\#sub_S$ is the *number* of sub-slits contained *within* the sub-slit separation, S.

Equation B.11 is really just the definite integral of the *component* DSI amplitudes at a point, P_Y, on the screen:

(Eq. B.13)

$$\int_{S=0}^{S=W} A_{PY}^*\,dS = \int_{S=0}^{S=W} A_O^* \cos(KS)\,dS = A_O^* \int_{S=0}^{S=W} \cos(KS)\,dS$$

And, substituting Equation B.12 for S in Equation B.13 gives:

(Eq. B.14) $\int_{S=0}^{S=W} A_{PY}^*\,dS = A_O^* \int_{S=0}^{S=W} \cos(K\,\#sub_S\,w)\,dS$

Taking the definite integral of Equation B.14:

(Eq. B.15) $$A_O{}^* \int_{S=0}^{S=W} \cos(K \#sub_s w)\, dS = A_O{}^* \sin \frac{(K \#sub_s w)}{Kw}$$

And, substituting Equation B.9 for $A_O{}^*$ in Equation B.15:

(Eq. B.16) $$\int_{S=0}^{S=W} A_{PY}{}^*\, dS = \frac{A_O}{\#sub_W} \; \frac{\sin(KS)}{Kw}$$

Since W = $\#sub_W$ w, we can re-write Equation B.16 as:

(Eq. B.17) $$\int_{S=0}^{S=W} A_{PY}{}^*\, dS = A_O \frac{\sin(KS)}{KW}$$

Evaluating the definite integral in Equation B.17, from S = 0 to S = W, we get:

(Eq. B.18) $$\int_{S=0}^{S=W} A_{PY}{}^*\, dS = A_O \frac{\sin(KW)}{KW}$$

By replacing K with Equation B.6, we can work our way back to an amplitude expression containing the phase-angle, δ. And, by squaring this amplitude, we get the expression for the SSI *intensity* at any point P_Y on the screen:

(Eq. B.19) $$I_{PY} = Io \frac{\sin^2(\delta/2)}{(\delta/2)^2}$$

This is the “classical” wave-model expression for the SSI intensity at *any* point, $P_{Y,}$ on the screen…and the one you’ll find in physics textbooks.

Equation B.19 demonstrates the SSI experiment can, indeed, be represented in terms of *component* DSI experiments.

INDEX

BIBLIOGRAPHY

There are, literally, thousands of physics books available, written for every conceivable audience, from grade school students to Nobel Prize winners. Below is a very short list of ones that I highly recommend, covering some of the topics contained in this book. There are dozens of others, equally good. Please use this bibliography as a starting point only; it's by no means an exhaustive list.

Introductory Level Books

Quantum Reality. Herbert, Nick. (Anchor Press/ Doubleday, 1985). If you're only going to read *one* book from this bibliography, make this the one. Written for a general audience in a delightful, non-technical (no math!) style, Herbert does a fantastic job of introducing not only QM theory itself, but many of the current interpretations in an objective, non-biased way. Highly recommended.

The Cosmic Code. Pagels, Heinz. (Simon and Schuster, 1982). Considered an instant classic, Pagels' book, intended for a general audience, introduces not only QM, but also relativity and particle physics. Contains excellent descriptions of the DSI experiment, Bell's Inequality, etc. Non-technical…that is, no math. Pagels' writing style conveys the wonder and excitement of modern physics.

Schrödinger's Kittens and the Search for Reality. Gribbon, John. (Little, Brown and Company, 1995). Another excellent, non-technical book, Gribbon covers much of the recent experimental research into "quantum

weirdness”, above and beyond the DSI and EPR experiments.

The Dancing Wu-Li Masters. Zukav, Gary. (William Morrow and Company, 1979). Written in the late 1970’s, and also intended for a general audience, this book provides a scientifically sound survey of QM and the implied “paradoxes” within. Careful, though: the book leans somewhat towards the “mystical” side, drawing comparisons between modern physics and ancient Buddhist philosophies.

The Tao of Physics. Kapra, Fritjof. (Shambhala Publications, 1975). Another scientifically accurate introduction to QM and its associated “paradoxes”, written for a general audience. But, readers beware! Kapra strongly promotes “quantum mysticism” throughout the text…with non-stop comparisons between modern physics and Eastern religious beliefs.

Intermediate Level Books

The Quantum Challenge. Greenstein, George and Zajonc, Arthur G. (Jones and Bartlett Publishers, 1997). If you’re only going to read *two* books from this bibliography, make this your second choice. Intended for an intermediate audience, some familiarity with quantum mathematics is desirable…but it’s well worth the reading, even if you skip some of the math. Covers many of the experiments demonstrating “quantum weirdness”, including detailed descriptions of proof of the existence of photons, how entangled photons and particles are created, the “delayed-choice”, “quantum eraser”, and quantum “non-demolition” experiments, etc., etc.

QED. Feynman, Richard. (Princeton University Press, 1985). Feynman won a Nobel Prize for his work on Quantum Electrodynamics (QED), and this book is his introduction to the theory, written for a general audience. Feynman's inimitable style as a lecturer—using humor, clarity, and commonsense—shines through on every page.

Physical Principles of the Quantum Theory. Heisenberg, Werner. (University of Chicago Press, 1930). Written for a popular audience, though containing some math, this book is surprisingly easy to read. Here, in his own words, are Heisenberg's explanations of the Uncertainty Principle, wave and matrix mechanics, and other topics of QM theory.

Speakable and Unspeakable in Quantum Mechanics. Bell, John S. (Cambridge University Press, 1987). A collection of essays and papers by the creator of Bell's Inequality. Some are aimed at a popular audience; others are highly technical papers from professional journals. Bell's innate charm and directness are evident throughout.

Advanced Level Books

The Feynman Lectures on Physics (Vol.3). Feynman, Richard. (Addison-Wesley Publishing Company, Inc., 1963). A series of undergraduate lectures given by the master himself, Volume 3 covers topics in quantum mechanics. By no means easy going, but well worth investing the time, these lectures are not for those afraid of math.

Rise of the New Physics (Vol. 1 and 2). D'Abro, A. (D. Van Nostrand Company, Inc., 1939). An incredible resource for learning the history and development of 20th century physics, including both relativity and quantum theory. Not for the faint of heart, D'Abro covers both subjects to an amazing depth, and will *teach* you the mathematics needed to really understand his explanations of wave equations, matrix mechanics, electron spin, and so forth. Commit the time to read both volumes, read them slowly, then read them again. I guarantee you'll be amazed at the depth of knowledge you'll gain.

The Principles of Quantum Mechanics. Dirac, P.A.M. (Oxford University Press, 1930). From the physicist who first predicted the existence of anti-matter, this is a graduate level book loaded with math. Dirac was the first to develop a relativistic quantum theory, combining both Schrödinger's wave and Heisenberg's matrix mechanics.

The Undivided Universe. Bohm, D. and Hiley, B.J. (Rutledge, 1993). Bohm first gained fame as the author of a classic textbook on QM, written from the Copenhagen point of view. Later, though, he had a change of heart…and this graduate level exposition of his new perspective was the result. Lots of math, lots of theory, but all written in an accessible style.

ACKNOWLEDGEMENTS

I gratefully acknowledge the many academic, theoretical and applied physicists with whom I've corresponded over the years. Their patience and willingness to share their time and expertise was truly overwhelming, and their comments, clarifications, and suggestions contributed greatly to Part 1 of this book.

Too numerous to name, each and every one embodied what is—to me—the fundamental "spirit" of science: to not only seek a better understanding of Nature, but to joyfully *share* that quest with others.

Any errors, shortcomings or inadvertent misrepresentations found in Part 1 are entirely mine.

The professional physicists and engineers with whom I've corresponded all expressed serious concerns about including, in an introductory book such as this, the very conjectural "toy" models presented in Part 2, as these are far from the more "mainstream" approaches to QM.

My decision to include Part 2 runs counter to their advice—and the responsibility for doing so is mine alone.