

Is Light a Wave or a Particle?



Schechtman on the reaction to his “discovery”:

“The head of my lab came to me smiling sheepishly, and put a book on my desk and said: ‘Danny, why don't you read this and see that it is impossible what you are saying’,” Dr Shechtman recounted in an interview with Technion.

The Israeli researcher was later told that he was a disgrace to the group and asked to leave.

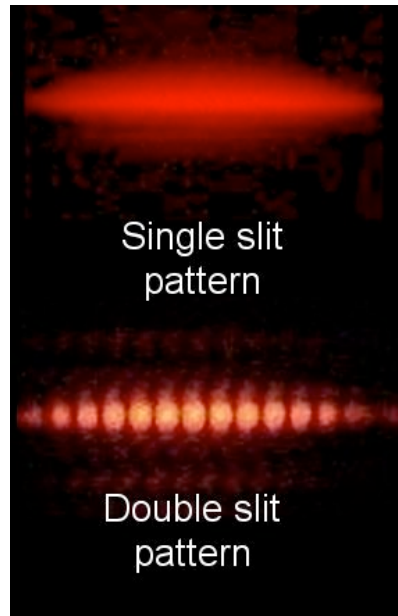
Your job in this course is to learn what it means to think scientifically: that does not mean to memorize “right answers,” but to learn how to debate possible answers & interpretations, and how to think about new observations and try to understand them.

Interference & Complementarity



Light is neither a wave nor a particle.

“Wave” and “particle” are two *aspects* of light, but they are “complementary” – we can choose to observe one or the other, but never both simultaneously.

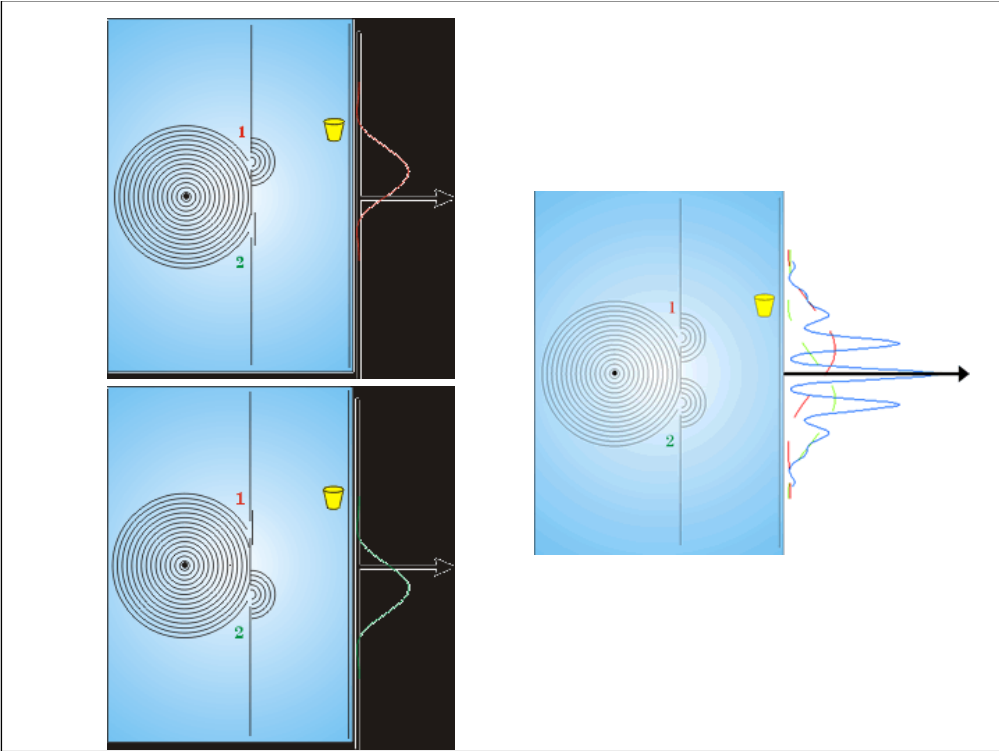


Single slit
pattern

Double slit
pattern

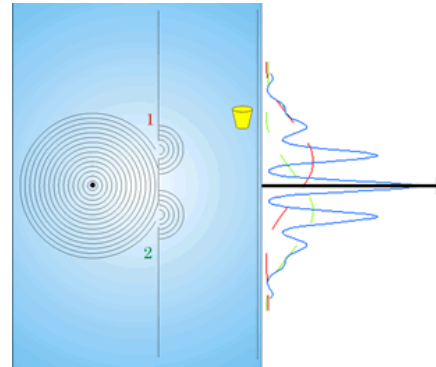
**Photon can land more or less
anywhere**

**There are points where many
photons land (“constructive
interference”) and points where no
photons land (“destructive
interference”)**



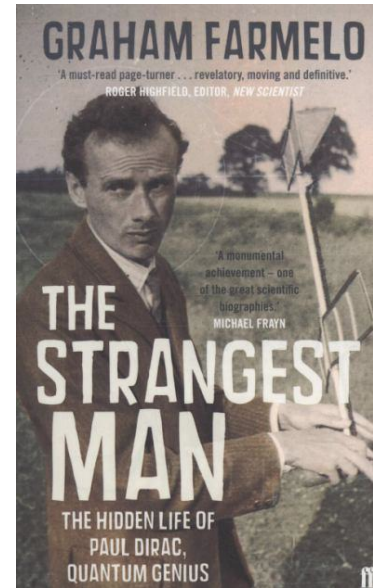
How to understand this after learning that light is made of photons?

Do photons from one slit “bump into” photons from the other slit and create this pattern? If so, then the pattern wouldn’t occur when only one photon was around at a time!



even if photons go through the apparatus one at a time!

**Each photon then interferes only with itself.
Interference between two different photons never occurs.**
-- Paul A.M. Dirac



So how does the photon *know* both slits are open?

Does the photon “take both slits at the same time”?

Even though the photon can only ever be detected in one place, somehow its “wave” is all over the place before that, and traverses both slits... *what is this wave?*

We could still say that “what’s waving” is an electric field... only, there’s something funny and non-local:

the field is everywhere right now, but if I see a photon, suddenly & immediately, the field everywhere else vanishes.

The modern interpretation (due to Max Born) is that the wave is a “wave of probability.”

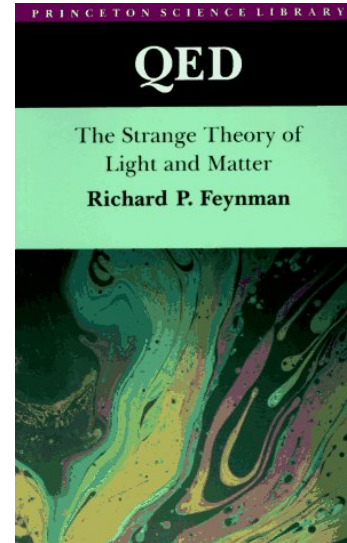
to think about: does this differ from the field interpretation?

An excellent reference

An analogy for quantum mechanics:

Let me explain it by analogy. The Maya Indians were interested in the rising and setting of Venus as a morning “star” and as an evening “star”—they were very interested in when it would appear. After some years of observation, they noted that five cycles of Venus were very nearly equal to eight of their “nominal years” of 365 days (they were aware that the true year of seasons was different and they made calculations of that also). To make calculations, the Maya had invented a system of bars and dots to represent numbers (including zero), and had rules by which to calculate and predict not only the risings and settings of Venus, but other celestial phenomena, such as lunar eclipses.

In those days, only a few Maya priests could do such elaborate calculations. Now, suppose we were to ask one of them how to do just one step in the process of predicting



Answering the question “why?”

Taking the example of the Maya one step further, we could ask the priest *why* five cycles of Venus nearly equal 2,920 days, or eight years. There would be all kinds of theories about *why*, such as, “20 is an important number in our counting system, and if you divide 2,920 by 20, you get 146, which is one more than a number that can be represented by the sum of two squares in two different ways,” and so forth. But that theory would have nothing to do with Venus, really. In modern times, we have found that theories of this kind are not useful. So again, we are not going to deal with *why* Nature behaves in the peculiar way that She does; there are no good theories to explain that.



Copenhagen Interpretation (Bohr, Heisenberg,...)

Bohr:

the task of physical theories is to predict the outcomes of experiments (results of observations).

If we get confused asking “is it a wave or a particle?” or “which path did it take?”, this is because we’re not asking answerable questions: we’re not asking about real measurements.

If you mean “when I place detectors in front of the two slits, which will fire?”, I can calculate the answer (at least the probabilities).

But if you have no detectors, and just ask “where is the photon?”, you’re not asking about anything observable, and physics has no answer.

Reality depends on the observer?

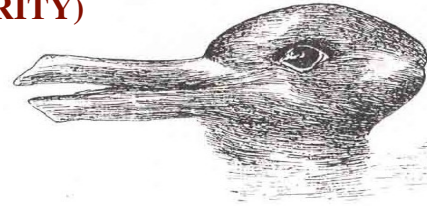
(Bohr:)

In other words, you must tell me *what experiment you plan to do* (will you measure which slit the particle goes through, or not?), before I agree to answer any questions.

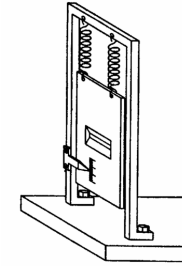
If your experiment isn't designed to measure particle-like properties (which slit), then the photon behaves like a wave.

If it is designed to measure particle-like properties, then the photon behaves like a particle.

“No experiment can be designed to do both at the same time”?!
(COMPLEMENTARITY)

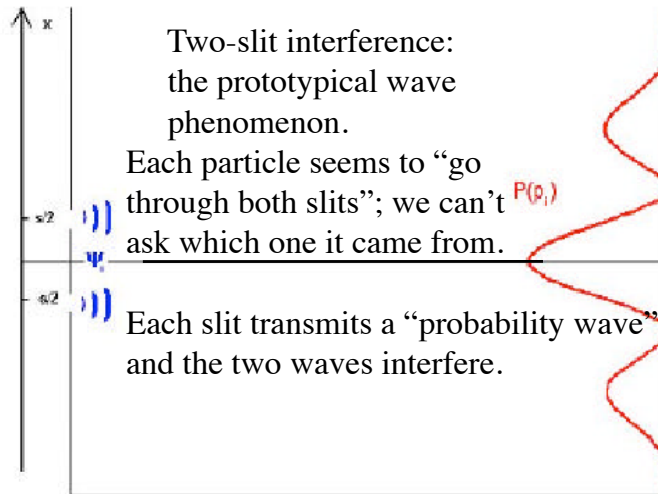


Bohr-Einstein debates

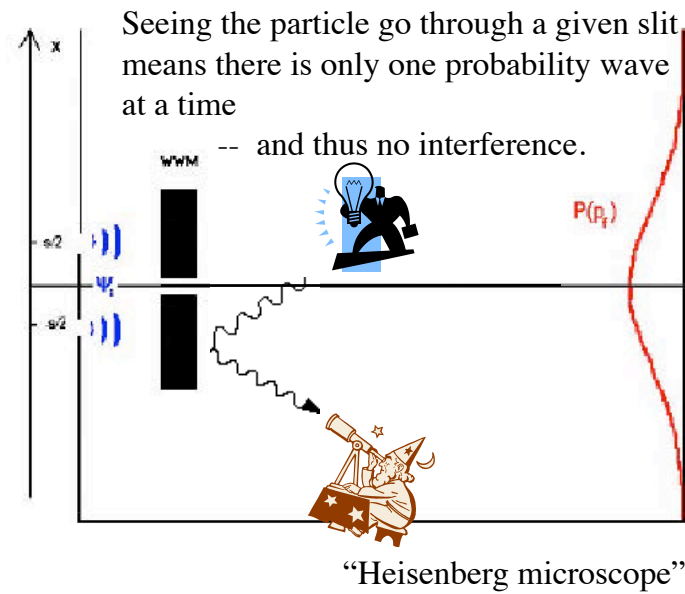


Cf. <http://www.youtube.com/watch?v=d303WjM7uUU>
for an unusual video recreating the debates...

The Bohr-Einstein debates



The Bohr-Einstein debates



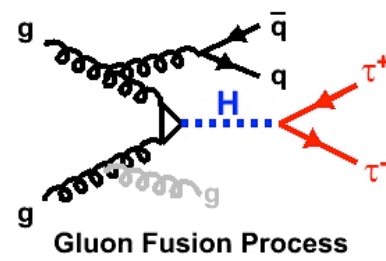
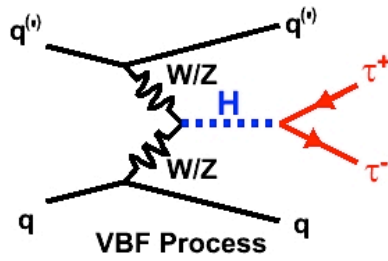
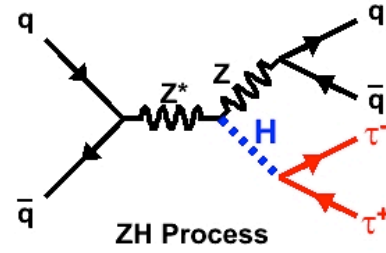
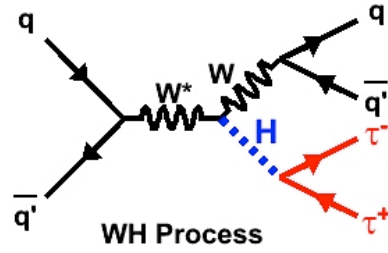
Feynman's Rules for interference

If *two or more indistinguishable* processes can lead to the same final event (particle could go through either slit and still get to the same spot on the screen), then ***INTERFERENCE OCCURS*** (add “amplitudes,” which could be negative and cancel out)

If multiple **distinguishable** processes occur, then you could imagine telling which; add *probabilities*; ***NO INTERFERENCE OCCURS.***

If there is any way – even in principle – to tell which process occurred, then there can be no interference (if you knew which slit the particle came from, you'd see a 1-slit pattern) !

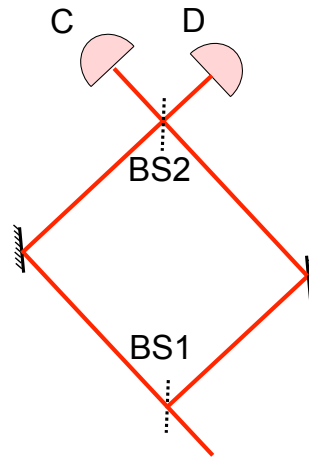
Feynman diagrams





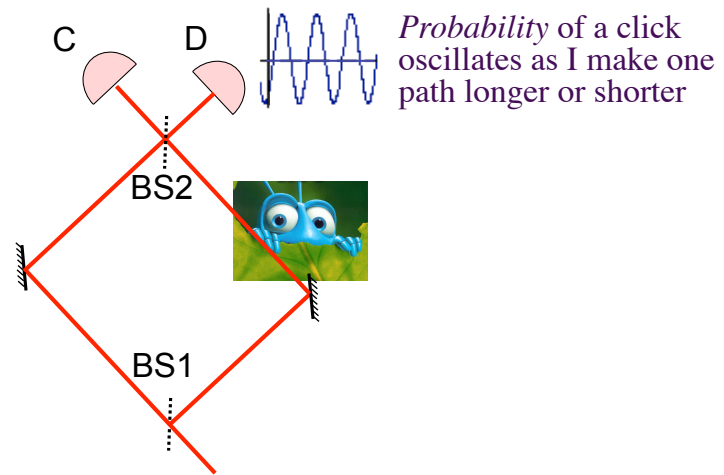
“Interferometer” - any device to measure interference

Interference occurs whenever a wave can take either of two (or more) paths to get somewhere...

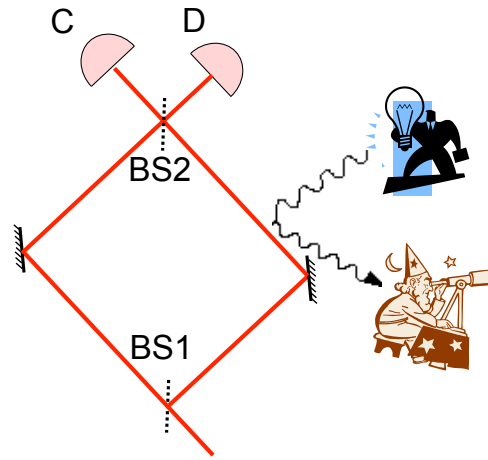


see <http://www.upscale.utoronto.ca/PVB/Harrison/MachZehnder/MachZehnder.html> for information on this type of interferometer

What would happen if someone were spying on your interferometer?



What would happen if the spy stopped looking?



If there is any way – even in principle – to tell which process occurred, then there can be no interference (if you knew which slit the particle came from, you'd see a 1-slit pattern) !

The “measurement problem”

What is a measurement?

What do I mean when I say “a measurement of which path occurred”?

John Bell:

It would seem that the [quantum] theory is exclusively concerned about 'results of measurement', and has nothing to say about anything else.

What exactly qualifies some physical systems to play the role of 'measurer'?

Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared?

Or did it have to wait a little longer, for some better qualified system...with a Ph.D.?

So, observations *change* the system under observation!*

Bohr:

Measurement means amplification of a quantum phenomenon by interaction with some “large” (classical) device
Msmt involves some *uncontrollable, irreversible disturbance*
We must treat the measuring device classically.

Wigner: Why must we? What will happen to us if we don't?

* - but don't overinterpret! Viz. Alan Sokal & Jean Bricmont, “Fashionable Nonsense,” and http://physics.nyu.edu/sokal/transgress_v2/transgress_v2_singlefile.html

The “Quantum Eraser”...

The quantum cowboy Marlan Scully and his friends:

Suppose we perform a which-path measurement using some “*microscopic*” pointer...

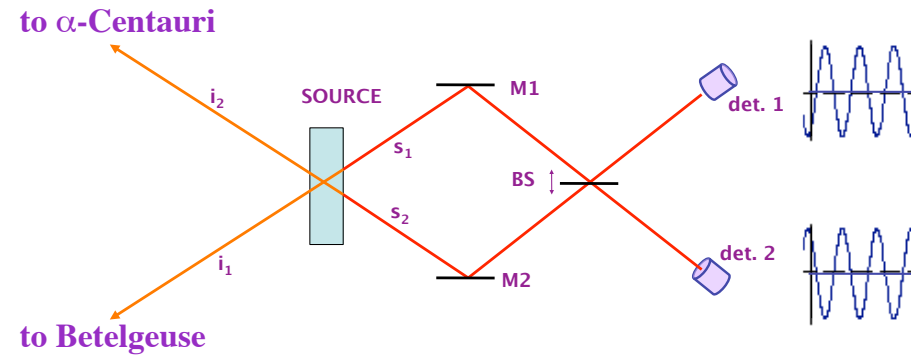
Is this really irreversible, as Bohr would have all measurements?

Is it sufficient to destroy interference?

Can the information be “erased,” restoring interference?



A microscopic measurement



The "i" photons provide which-path information, and destroy the interference.
Can this information be "erased"?

Indistinguishability

This still confuses even “expert” physicists,
but when we say interference doesn’t occur
between “distinguishable” paths/processes,
*we mean if there is any way, even in principle,
that these paths could be distinguished, then
there can be no interference!*

" Quantum seeing in the dark "

(AKA: "Interaction-free" measurement,
aka "Vaidman's bomb")

A. Elitzur and L. Vaidman, Found. Phys. **23**, 987 (1993)

P.G. Kwiat, H. Weinfurter, and A. Zeilinger, Sci. Am. (Nov., 1996)

Problem:

Consider a collection of bombs so sensitive that a collision with any single particle (photon, electron, etc.) is guaranteed to trigger it.

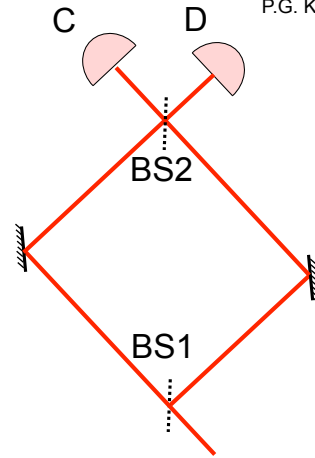
Suppose that certain of the bombs are defective, but differ in their behaviour in *no way* other than that they will not blow up when triggered.

Is there any way to identify the working bombs (or some of them) without blowing them up?

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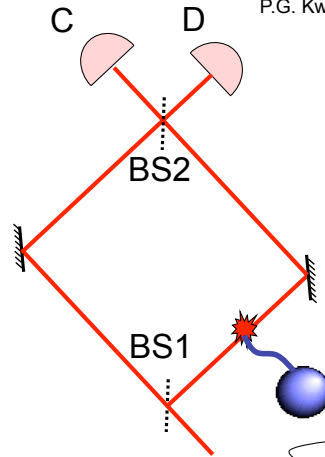


Trigger absent/ineffectual:
Only detector C fires

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Trigger absent/ineffectual:
Only detector C fires

Trigger working:
"boom!" 1/2
C 1/4
D 1/4

*The bomb must be there... yet
my photon never interacted with it.*

Fanciful musing about this

Many feel that QM implies a tree falling in an empty forest makes no sounds.

Not only is this an inappropriate conclusion, but:

- **QM says you can tell that a tree *would have made a sound had it fallen*, even if it doesn't fall!**
- **QM is not a theory of what happens, but of all the possible things which could happen.**