FINAL EXAM SCHEDULED:
Weds. Dec 12, 7pm - 10pm
in BN2N (320 Huron, 2nd floor)

The moving finger writes;
and having writ, moves on:
nor all your piety nor wit
shall lure it back to cancel half a line...

(Omar Khayyam, Rubaiyat)

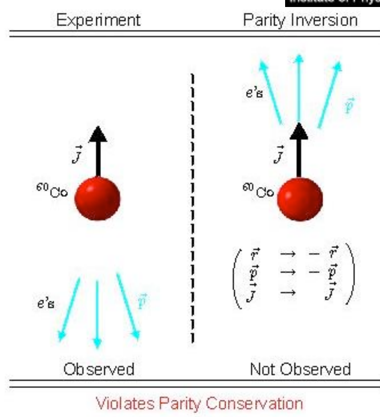
After all this time trying to figure out why the laws seemed symmetric when everyday life doesn't...

It turns out the laws *aren't* quite symmetric!

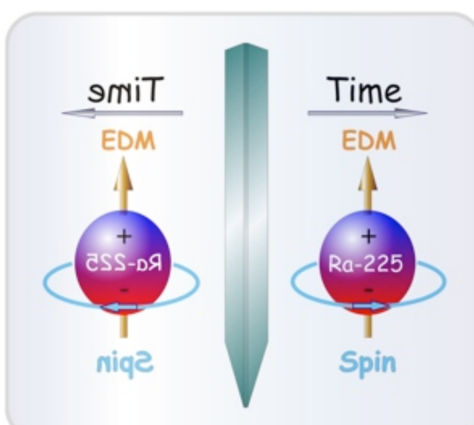
(and now we're even *more* surprised.)

Violations of symmetry at the microscopic level

"Parity Violation"



Violations of symmetry at the microscopic level



Viewpoint: Particle Decays Point to an Arrow of Time

Michael Zeller, *Department of Physics, Yale University, New Haven, CT 06520, USA*

Published November 19, 2012 | *Physics* **5**, 129 (2012) | DOI: 10.1103/Physics.5.129

An experiment studying *B* meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.

Time moves irrevocably in one direction. Things get old, decay, and fall apart, but they rarely ever reassemble and grow young. But at the particle level, time's arrow is not so clearly defined. Most collisions and other particle interactions look the same whether run forwards or backwards. Physicists have, however, identified a few reactions that appear to change when time is reversed, but the reasoning has assumed certain relations between fundamental symmetries of particle physics. The BaBar collaboration has now observed time-reversal violation directly and unambiguously in decays of *B* mesons. The measured asymmetry, reported in *Physical Review Letters* [1], is statistically significant and consistent with indirect observations.

In trying to understand the nature of particle interactions, observing the behavior of those interactions under different symmetry transformations has proven invaluable in formulating and verifying the fundamental theory. It is well known, and has been experimentally shown, that the strong and electromagnetic interactions are unchanged when viewed in a mirror world, in which particle positions are reflected ($\vec{r}$ to $-\vec{r}$). In contrast, experiments in 1956 [2] demonstrated that the weak interaction is not invariant under such parity inversion (*P*). A decade later, researchers found evidence in *K* meson decays [3] that weak interactions may also violate a combination of parity inversion with charge conjugation (*C*), where particles are interchanged for antiparticles. Physicists continue to study *CP* violation, in part to explore whether it can explain the dominance of matter over antimatter in the universe. But a related symmetry, time inversion (*T*), has been more elusive. It involves running an experiment backwards (t to $-t$) and

Observation of Time-Reversal Violation in the B^0 Meson System
J. P. Lees et al. (The BABAR Collaboration)
Phys. Rev. Lett. **109**, 211801 (2012)
Published November 19, 2012 | PDF (free)

+Enlarge image

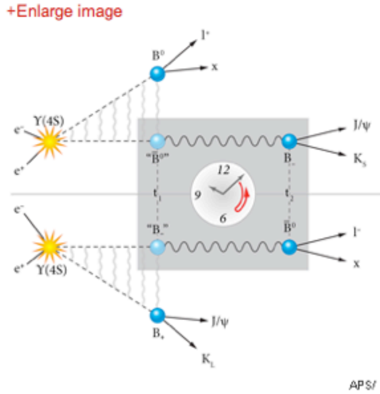


Figure 1 Electron-positron collisions at SLAC produce a Υ(4*s*) resonance that results in an entangled pair of *B* mesons. When one meson decays at time t_1 , the identity of the other is "tagged" but not measured specifically. In the top panel,

Several arrows of time (?)

Entropy increases (water runs downhill, etc).

We remember the past, not the future.

The universe is expanding, not contracting.

Schrödinger's cat is in a superposition *before* we observe him, but not after (?)

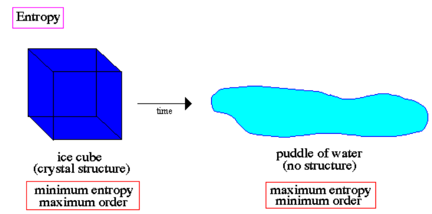
Unclear to this day whether these are all related, or perhaps independent. Also unclear whether the *microscopic* violation of time-reversal symmetry is responsible for these macroscopic violations or not...

Some earthly consequences

• Mechanical energy can dissipate into heat, but the reverse doesn't occur.

• Heat *can* be used to do work -- but always inefficiently.

• A particular system may get more ordered with time - its entropy goes down. (When we cool water and it freezes into ice crystals, this happens.)



But *total* entropy is going up -- to cool the water, we increase the overall entropy of the universe with our fridge's exhaust.

• The "energy crisis" is really all about entropy. Energy is conserved, but low-entropy, ordered systems are hard to come by.

So, instead of a Department of Energy, perhaps we need a ...

What is Quantum Mechanics?

The theory of atoms?

The theory of atoms and photons?

The theory of really small stuff?

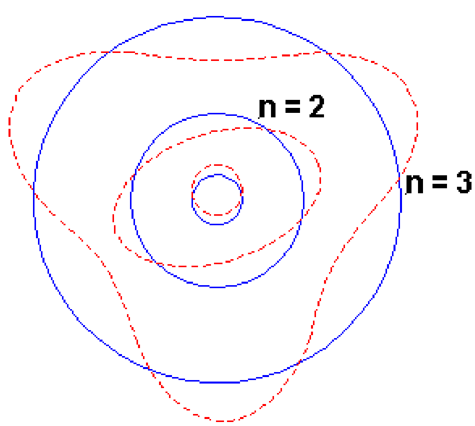
If not "the theory of everything," then at least *the framework* in which we (currently) believe the theory of everything would have to fit.

(I.e.: Einstein's relativity "corrected" Newton's laws -- but both discussed things that could be described as having a given position at a given time. QM says even the question is wrong -- reality is not *about* "positions" et cetera)

You recall "waves of probability"

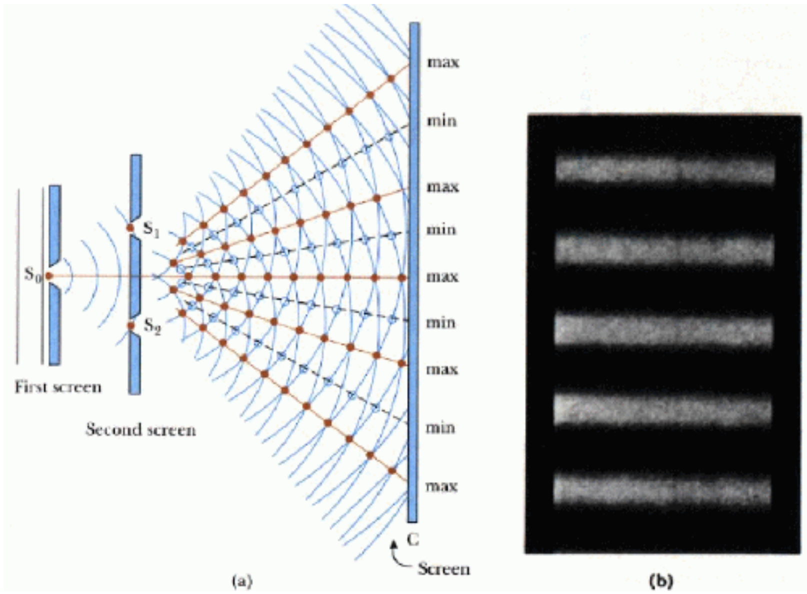
If light waves act like particles sometimes, then maybe particles of matter also act like waves sometime.

Waves exhibit *resonances* – only specific frequencies they can vibrate at.



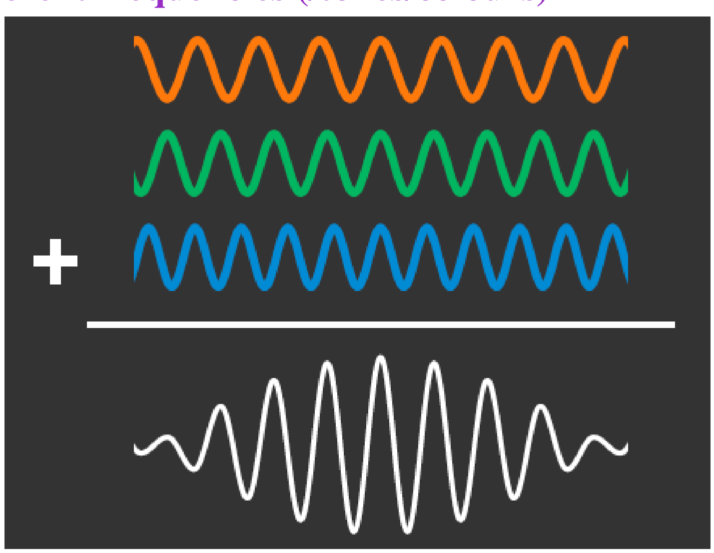
The standing de Broglie waves set up in the first three Bohr orbits.

(and you recall interference)



An ideal wave goes on forever

But since waves *interfere*, we can make a "wave packet" by adding different frequencies (/tones/colours)



The shorter a note, the more frequencies it must really contain!

What would "different frequencies" mean for an electron?

a. Different colours
b. Different masses
c. Different speeds
d. Different spins

Superposition

If the wave represents probabilities, then the sum of two waves represents even more probabilities...

If Wave(wavelength 1) has momentum 1 [but could be anywhere] and Wave(wavelength 2) has momentum 2 [but could be anywhere] then

Wave(wavelength 1)+Wave(wavelength 2)

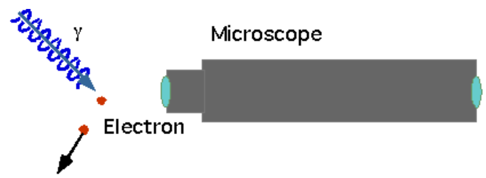
means

- **50% chance of having momentum 1**
- **50% chance of having momentum 2**
  - **but some idea of (roughly) where it is.**

(This is one way of looking at the uncertainty principle: to have any idea where something is, you must accept some uncertainty in its momentum)

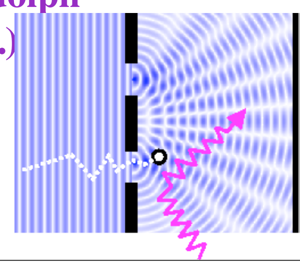
Uncertainty & the Heisenberg Microscope

Like Einstein, let's think about what it means *physically* to observe:



Heisenberg: the act of measuring position changes momentum (and vice versa).

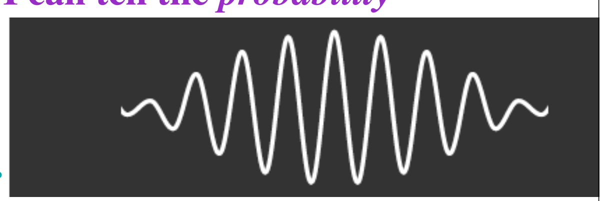
More rigorous: position & momentum could never have even *had* definite values at the same time (see Rudolph preprint I shall post on the web for more on this...)



The 1-particle quantum state

If a classical description of a 1-particle state is
"It's at position x and has momentum p"

The quantum description of the state is
"the *probability amplitude* to be at *each* position x is Ψ(x)"
[The position is uncertain, but I can tell the *probability* to be at x by squaring Ψ(x)]



Note that p isn't listed separately.

That's because the *wavelength* of Ψ(x) already tells you p; this is why we can't independently specify x and p...

THIS "WAVE FUNCTION" OR "STATE VECTOR" IS DEEMED TO BE A* COMPLETE *DESCRIPTION (SUFFICIENT TO PREDICT* ANYTHING*)

But what is this uncertainty?

Bohr: “physics is not about reality,
but about what we can say about reality.”

Wave behaviour and particle behaviour are “complementary”;
if you put a detector at one slit, you observe particles;
if you build an interferometer, you observe waves.

Before making any predictions, Bohr insists on knowing
the entire experimental setup (including measuring devices).

But what of reality??

Einstein:
Come on, there must be some meaning
to position & momentum
whether or not I measure them!

Bohr:
Why, if you can’t measure both?
I’m just doing the same thing you did when you started
relativity by pointing out “measurement is physical.”
You have to think about the measurement you’re doing.

Einstein: a good joke shouldn’t be repeated too often.

Is this the same as relativity or not?

Recall statistical thermodynamics

Thermodynamics is an excellent theory, and predicts the expansion of heated gas, the efficiency of engines, et cetera; but it refuses to tell us *exactly where* any given air molecule is.

It is *correct*, but not *complete*.

Maybe QM is the same. A correct, *statistical*, description of how many identically prepared particles behave, but which is missing some "hidden variables" that tell us how each *individual* particle behaves...

The general quantum state

If a classical description of a state of any system (the universe) is
"If you measured all the measurable things -- position, momentum, and so on of every particle in existence -- they'd have the following list of values: $p_1,x_1,p_2,x_2,......$"

The quantum description of the state is
"the *probability amplitude* to be in each of the distinguishable states labelled by $x_1,x_2,...$ is $\Psi(x_1,x_2,...)$"

Again: $p_1,p_2,...$ can't be listed separately. That's because the *wavelength* of $\Psi(x_1,x_2,...)$ already tells you the p's...

Note that there is no longer a separate description of "the reality for particle 1" and "the reality for particle 2" -- there is one big function for the probability of *everything*. We will keep returning to this issue of "entanglement," the oddest thing about QM...

So what happens when I measure something?

The position and velocity couldn't have both been known, but I get an answer whichever one I measure... and even if I measure position, where will it be a minute later??

The problem we're still arguing about today:
What does it mean that it's "impossible" to know both?

- **Particles really have definite positions & momenta,**
  but we don't know how to measure them? And QM is just a theory of the "big picture," like thermodynamics?
- **Particles don't actually have definite positions & momenta?**
  (or any other definite properties, for that matter?)

  The quantum state "collapses" randomly when we look at it?

If a tree falls in a forest, and everyone is wearing iPods ...

"I like to think that the moon is there even when I am not looking at it."- Albert Einstein

Reality?

- Bohr: "There is no quantum world. There is only an abstract quantum mechanical description."
- Heisenberg: "The atoms or the elementary particles are not real; they form a world of potentialities... rather than one of things or facts."
- Many modern physicists: There is no *classical* world – there is just the illusion that the (truly quantum) world is classical...

A few possible perspectives...

Copenhagen interpretation

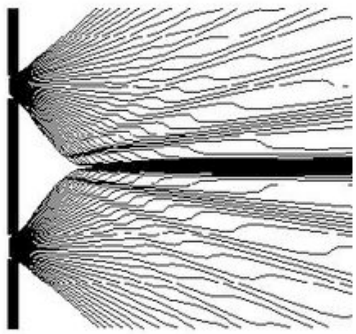
From Wikipedia, the free encyclopedia

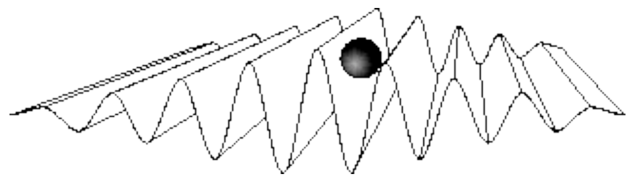
The **Copenhagen interpretation** is one of the earliest and most commonly taught interpretations of quantum mechanics.[1] It holds that quantum mechanics does not yield a description of an objective reality but deals only with probabilities of observing, or measuring, various aspects of energy quanta, entities which fit neither the classical idea of particles nor the classical idea of waves. According to the interpretation, the act of measurement causes the set of probabilities to immediately and randomly assume only one of the possible values. This feature of the mathematics is known as wavefunction collapse. The essential concepts of the interpretation were devised by Niels Bohr, Werner Heisenberg and others in the years 1924–27.

Wiki's view of Copenhagen...

1. A system is completely described by a wave function ψ, representing the state of the system.
2. The description of nature is essentially probabilistic, with the probability of an event related to the square of the amplitude of the wave function related to it. (The Born rule, after Max Born)
3. It is not possible to know the value of all the properties of the system at the same time; those properties that are not known with precision must be described by probabilities. (Heisenberg's uncertainty principle)
4. Matter exhibits a wave–particle duality. An experiment can show the particle-like properties of matter, or the wave-like properties; in some experiments both of these complementary viewpoints must be invoked to explain the results, according to the complementarity principle of Niels Bohr.
5. Measuring devices are essentially classical devices, and measure only classical properties such as position and momentum.
6. The quantum mechanical description of large systems will closely approximate the classical description. (The correspondence principle of Bohr and Heisenberg.)

de Broglie/Bohm: “pilot waves”





Yves Couder’s classical particle-waves