What is the Quantum Enigma

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Quantum Mechanics is very amazing. It has features which are very counterintuitive. It is extremely successful. But if you survey leading physicists, you will find that many are not totally satisfied.

Bruce and Fred mention some names in their book and lectures. I did my own little survey: Totally* satisfied:

1. Banks, UCSC (just inducted into American Academy), Shastry, UCSC (winner of Onsager prize of American Physical Society), Dine (American Academy)
2. Susskind (Stanford; American Academy, National Academy, Sakurai Prize)
3. Nathan Seiberg (Institute for Advanced Study; National Academy, MacArthur Fellow...)
4. The late Sidney Coleman (Harvard)

$^* =$ Some improvement in interpretation may be possible.

Less satisfied*:

1. Ed Witten (Institute for Advanced Study; National Academy, MacArthur Winner, Fields Medal...)
2. Steve Weinberg (UT Austin; Nobel Prize winner)
3. Steve Shenker (Stanford, American Academy, MacArthur Fellow..)
4. G. 't Hooft (Utrecht, Nobel Prize winner)

$* =$ Some serious reformulation may be needed, especially to understand the role of probability.

None of these physicists believe that the point is to replace quantum mechanics with classical mechanics. If anything, they believe that we may encounter a formulation of quantum mechanics which makes no reference to classical mechanics, and from which classical mechanics will emerge.

This point is put forcefully by Sidney Coleman in his famous lecture “Quantum Mechanics in Your Face", when he says that classical mechanics should be understood simply as a limiting case of quantum mechanics, *not the other way around!*.

What did the Copenhagen physicists think?

- They were quite conscious of the fact that human intelligence evolved to deal with problems like chasing prey, escaping predators, avoiding accidents... We have no need for an understanding of the laws governing atoms and things smaller to survive.
- As a result, they did not take for granted that *human beings should be able to understand the laws of submicroscopic physics*. That we are able to guess the laws of quantum mechanics, and that they work – on cosmic distance scales and scales thousands of times shorter than an atomic nucleus – is, to put it mildly, remarkable.
- As a result, they did not see that the laws need match neatly our day to day experience (“classical physics").
- They thought that Schrodinger did not understand quantum mechanics (see A. Pais, *Bohr*).

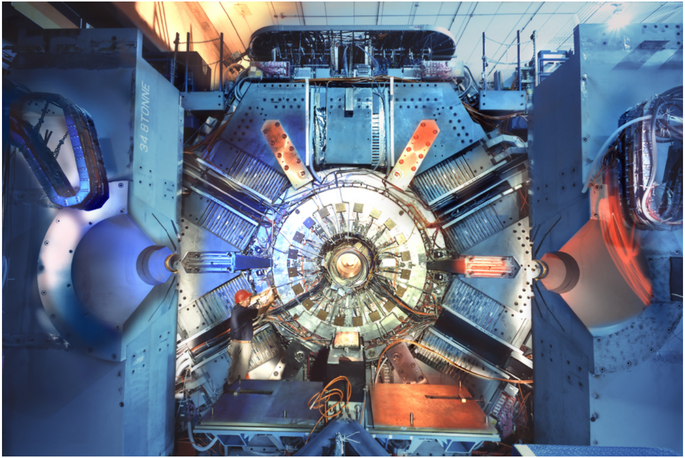
Shut Up and Calculate – and the Copenhagen Interpretation

Serious discussion of quantum mechanics has moved well beyond "Copenhagen". Textbooks, for the most part, still adopt a distilled version of Copenhagen, because it serves as a convenient shorthand for *almost* all experiments where quantum mechanics is important. The rules can be written down in less than a page. A few go a bit further. Bruce and Fred are right when they say that most physicists are not bothered by these questions and don't give them much thought.

Quantum Realms and Quantum Measurements

Old fashioned textbooks – the ones Bruce, Fred and I were raised with, often depict measurements schematically as being made by a human eye. Needless to say, this is not the nature of modern measurements, which are made with complex instruments, the data recorded electronically. We can speak of these collectively as robots. The data is never examined by any human observer immediately (the measurements are made in microseconds or less; large fractions are never examined, and individual events or observations are rarely examined individually).

The Babar Detector at SLAC:



This experiment looked for violation of *Time Reversal Invariance* (CP), and successfully studied it (Nobel Prize, 2009). Did an *interference measurement* (much like Fred and Bruce's boxes). Studied two types of particles (B and its antiparticle, $\bar{B}$). Very different properties (e.g. masses) Certain types of measurements identified B; certain types $\bar{B}$, certain types $B \pm \bar{B}$ (like the boxes; if in such a *state*, can't say whether B or $\bar{B}$; but can then measure which).

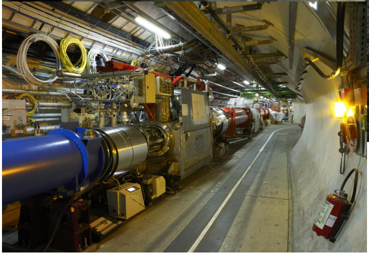
All of these experiments were conducted by robots. In many cases, the measurements were *blinded*; the results were analyzed purely by robots until, months later, the output was examined by different experimenters.

It is very hard to see that human consciousness played any role in these measurements.

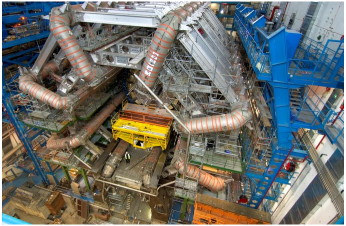
The LHC at CERN:

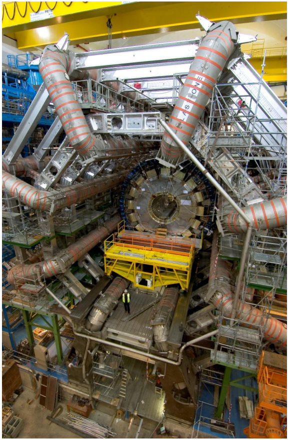
2 in 1 superconducting dipole magnet being installed in the CERN tunnel

ATLAS project



ATLAS, one of the two large detectors at the LHC (Other: CMS; ALICE will study heavy ion collisions)





Muon superconducting Toroids in the ATLAS Detector at the LHC

1. The stored energy in the beams is roughly to the kinetic energy of an aircraft carrier at 10 knots (stored in magnets about 16 times larger)
2. There are about a billion collisions per second in each detector.
3. The detectors store only around 100 collisions per second.
4. The total amount of data to be stored will be 15 petabytes (15 million gigabytes) a year.
5. It would take a stack of CDs 20Km tall per year to store this much data.

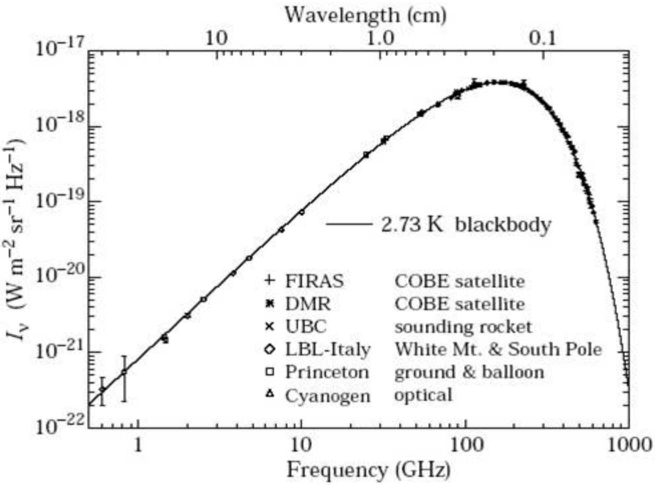
There are thousands of people involved in these experiments, but still there isn't enough time for each recorded event to interact with any “conscious" being.

When does the quantum measurement happen?

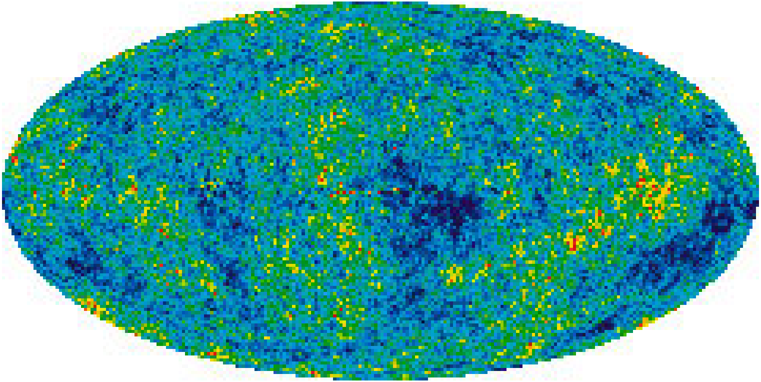
Another arena: The *Universe*

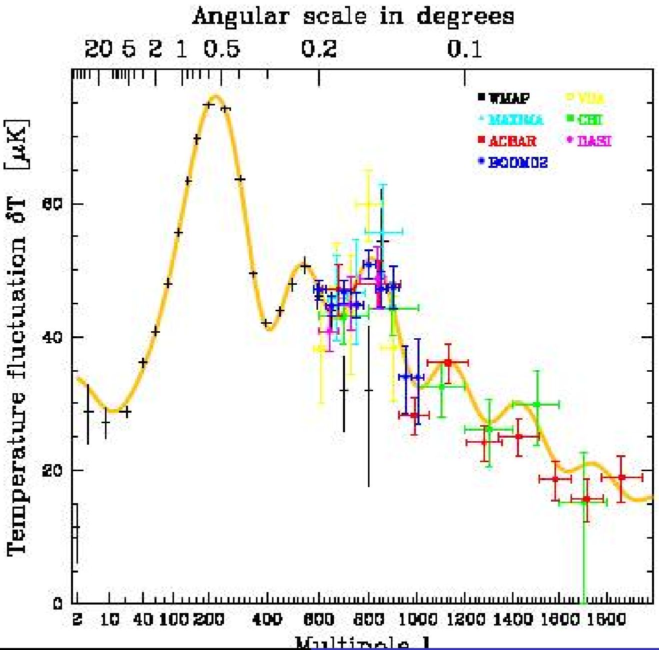
For almost 50 years, astronomers and physicists have studied the Cosmic Microwave Background Radiation (CMBR). A beautiful quantum phenomenon. Fred and Bruce may have told you about Planck's great discovery (the origin of the term "Planck's constant", which enters the Schrodinger equation and defines the scale of quantum phenomena) of the "black body radiation". Solved one of the great puzzles of classical physics – what is the spectrum of electromagnetic energy radiated by a body at a given temperature.

This background radiation, which originated $100,000$ years after the big bang, is *the most perfect blackbody known*.


Wavelength (cm)
10
1.0
0.1
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
I_ν (W m^{-2} sr^{-1} Hz^{-1})
2.73 K blackbody
+ FIRAS COBE satellite
DMR COBE satellite
UBC sounding rocket
LBL-Italy White Mt. & South Pole
Princeton ground & balloon
Cyanogen optical
1
10
100
1000
Frequency (GHz)

But while interesting, this is not the most striking quantum mechanical aspect of this radiation. Over the last 15 years, what has been measured is slight differences in temperature (parts in 100,000) in different parts of the sky. Example of a map (from the WMAP satellite):





Angular scale in degrees
20 5 2 1 0.5
0.2
0.1
WMAP
VSA
MAXIMA
CBI
ACBAR
DASI
BOOM02
Temperature fluctuation δT [μK]
0
20
40
60
2 10 40 100 200
400 600 800 1000 1200 1400 1600 1800
Multipole l

What does this have to do with quantum mechanics and measurement? It turns out that these variations in the temperature resulted from quantum mechanical fluctuations at times less that 10^{-14} seconds after the big bang.

These fluctuations are important – not only are they measured, but they are what lead to the structure we see in the universe around us – galaxies, clusters of galaxies (and stars, planets, people). Without them we wouldn't be here. Nor our ancestors. Nor the planet we live on...

This is one of the most spectacular discoveries in modern science (Nobel prize for George Smoot, probably one more). We have developed an exquisite (though not yet complete) understanding of the universe and its history.

Who measured these fluctuations? You, me? My grandmother?

What is a Measurement?

The pattern of my questions should be obvious, though I am not going to give you a simple, pat answer – I invite you to think about these questions, to learn and read more.

In the *Copenhagen Interpretation* (e.g. Born, Bohr, von Neumann) measurement occurs when a microscopic object interacts with a macroscopic object.

The notion of the "collapse of the wave function", something outside of the description of quantum mechanics and the Schrodinger equation, while a convenient shorthand for quantum mechanics textbooks, has long been rejected by most workers in quantum mechanics (Bohr explicitly suggested that quantum mechanics ceased to describe the system after the subject of the observation interacted with the measuring instrument).

Instead, the system (of 10^{30} atoms, in the case of the detectors above and the B meson) is described by a huge wave function. After the B meson or other particle interacts with the detector, the *whole system* is still described by a single wave function. Initially, the wave function is simple; after some time (nanosceconds) the wave functions are hopelessly entangled. No conceivable measurement can disentangle the two, and see quantum interference after that (a computer the size of the universe would not have adequate capability).

I know Bruce and Fred have/will tell you about this a bit.

Is this weird? Is it satisfying?

I don't know about you, but when I was in school, inclined planes, falling artillery shells, and the other stuff in elementary physics textbooks seemed pretty boring. Only when I learned about quantum mechanics (from a wonderful old text by Messiah, but also from a book by Jammer called *The Conceptual Development of Quantum Mechanics* did I feel that Physics was interesting (perhaps this is a product of being a child of the '70's; how could I hold me head up if all I studied was some mechanistic system?).

If I survey my colleagues and ask if they are satisfied, as I said, I get mixed responses. Quantum mechanics is surely right. Is it complete? Will something radically change when it is understood better?

Contexts in which these questions might be meaningful

Most agree that it is only with general relativity that these questions become exciting and potentially meaningful. In general relativity, *space and time themselves are subject to quantum fluctuations*.

- String theory – a theory of quantum gravity. Might have thought that it would imply some modification of quantum mechanics. But seems completely conventional. (Witten) E.g. Hawking's famous problem of black holes – that the coherence can't be maintained, even in principle – is resolved.
- Cosmology: at some point, need to understand the wave function of the universal as a whole. What does this mean? What does it mean to associate probabilities with this wave function? The answers to these questions are not known. Many think that their resolution will require a deeper understanding of quantum mechanics; some a reformulation.

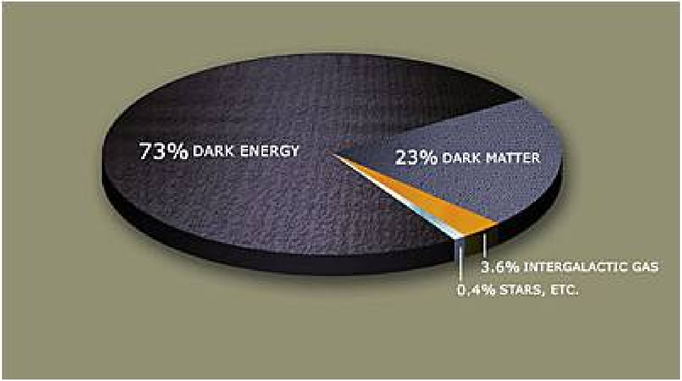
All of those in my survey believe that the resolution to these questions will lie, not in bringing the subject closer to classical physics, but to endowing it with its own language, from which classical physics – the physics of our day to day experience, will emerge.

To quote Sidney Coleman, “the problem is not the interpretation of quantum mechanics - it is the interpretation of classical mechanics".

The Real Skeleton in Our Closet

There is nothing wrong, for any operational situation, with our understanding of quantum mechanics. If anything, it is too successful. These problems of interpretation are philosophically entertaining, but of no practical importance, except perhaps for cosmology. There is no skeleton in this closet.

But physicist have at least one. This is connected with the *dark energy*; and this does have something to do with quantum mechanics.


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

We don’t know what the dark matter is with certainty, but we have a number of promising theories and experiments are searching for it.

But the dark energy is weird. You might think that there is a lot of it, but it is actually strange that there is *so little*.

In quantum mechanics, every possible state of a photon, an electron, a proton or neutron, has a little energy – this is because of the uncertainty principle. In other words, even if we don't "see" a photon with enough energy to knock us over, we can't say that there is zero electric and magnetic field associated with that photon. This is an example of the uncertainty principle – it comes right out of solving the Schrodinger equation.

Now there are a lot of different kinds of photon – one for every possible frequency and polarization. So one's naive guess is that the energy density of the universe – this dark energy – should be, to paraphrase Carl Sagan, billions and billions (and billions and billions and billions and billions..) of times larger than it is. We can fix our theories to account for this, but not in any way which is very convincing. This problem leads, for example, to the *multiverse* hypothesis (due to Tom Banks, here, and Steven Weinberg, Andrei Linde) that you may have heard about from Brian Green's latest book and public appearances.