Quantum Physics – Part I

Some Basic Ideas from Quantum Physics …

- **UNCERTAINTY**

- **CO-LOCATION**

- **ENTANGLEMENT**

- **LIGHT THEORY**

Richard P. Feynman – Nobel Lecture

Nobel Lecture, December 11, 1965

The Development of the Space-Time View of Quantum Electrodynamics

We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover all the tracks, to not worry about the blind alleys or to describe how you had the wrong idea first, and so on. So there isn't any place to publish, in a dignified manner, what you actually did in order to get to do the work, although, there has been in these days, some interest in this kind of thing. Since winning the prize is a personal thing, I thought I could be excused in this particular situation, if I were to talk personally about my relationship to quantum electrodynamics, rather than to discuss the subject itself in a refined and finished fashion. Furthermore, since there are three people who have won the prize in physics, if they are all going to be talking about quantum electrodynamics itself, one might become bored with the subject. So, what I would like to tell you about today are the sequence of events, really the sequence of ideas, which occurred, and by which I finally came out the other end with an unsolved problem for which I ultimately received a prize.

I realize that a truly scientific paper would be of greater value, but such a paper I could publish in regular journals. So, I shall use this Nobel Lecture as an opportunity to do something of less value, but which I cannot do elsewhere. I ask your indulgence in another manner. I shall include details of anecdotes which are of no value either scientifically, nor for understanding the development of ideas. They are included only to make the lecture more entertaining.

I worked on this problem about eight years until the final publication in 1947. The beginning of the thing was at the Massachusetts Institute of Technology, when I was an undergraduate student reading about the known physics, learning slowly about all these things that people were worrying about, and realizing ultimately that the fundamental problem of the day was that the quantum theory of electricity and magnetism was not completely satisfactory. This I gathered from books like those of Heitler and Dirac. I was inspired by the remarks in these books; not by the parts in which everything was proved and demonstrated carefully and calculated, because I couldn't understand those very well. **At the young age what I could understand were the remarks about the fact that this doesn't make any sense, and the last sentence of the book of Dirac I can still remember, "It seems that some essentially new physical ideas are here needed." So, I had this as a challenge and an inspiration. I also had a personal feeling, that since they didn't get a satisfactory answer to the problem I wanted to solve, I don't have to pay a lot of attention to what they did do.**

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But, as I was stupid, so was Professor Wheeler that much more clever. For he then went on to give a lecture as though he had worked this all out before and was completely prepared, but he had not, he worked it out as he went along. First, he said, let us suppose that the return action by the charges in the absorber reaches the source by advanced waves as well as by the ordinary retarded waves of reflected light; so that the law of interaction acts backward in time, as well as forward in time. I was enough of a physicist at that time not to say, "Oh, no, how could that be?" For today all physicists know from studying Einstein and Bohr, that sometimes an idea which looks completely paradoxical at first, if analyzed to completion in all detail and in experimental situations, may, in fact, not be paradoxical. So, it did not bother me any more than it bothered Professor Wheeler to use advance waves for the back reaction - a solution of Maxwell's equations, which previously had not been physically used.

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Many different physical ideas can describe the same physical reality. Thus, classical electrodynamics can be described by a field view, or an action at a distance view, etc. Originally, Maxwell filled space with idler wheels, and Faraday with fields lines, but somehow the Maxwell equations themselves are pristine and independent of the elaboration of words attempting a physical description. The only true physical description is that describing the experimental meaning of the quantities in the equation - or better, the way the equations are to be used in describing experimental observations. This being the case perhaps the best way to proceed is to try to guess equations, and disregard physical models or descriptions. For example, McCullough guessed the correct equations for light propagation in a crystal long before his colleagues using elastic models could make head or tail of the phenomena, or again, Dirac obtained his equation for the description of the electron by an almost purely mathematical proposition. A simple physical view by which all the contents of this equation can be seen is still lacking.

Therefore, I think equation guessing might be the best method to proceed to obtain the laws for the part of physics which is presently unknown. Yet, when I was much younger, I tried this equation guessing and I have seen many students try this, but it is very easy to go off in wildly incorrect and impossible directions. I think the problem is not to find the *best* or most efficient method to proceed to a discovery, but to find any method at all. Physical reasoning does help some people to generate suggestions as to how the unknown may be related to the known. Theories of the known, which are described by different physical ideas may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown. For different views suggest different kinds of modifications which might be made and hence are not equivalent in the hypotheses one generates from them in ones attempt to understand what is not yet understood. I, therefore, think that a good theoretical physicist today might find it useful to have a wide range of physical viewpoints and mathematical expressions of the same theory (for example, of quantum electrodynamics) available to him. This may be asking too much of one man. Then new students should as a class have this. If every individual student follows the same current fashion in expressing and thinking about electrodynamics or field theory, then the variety of hypotheses being generated to understand strong interactions, say, is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view of field theory - who will find it? Only someone who has sacrificed himself by teaching himself quantum electrodynamics from a peculiar and unusual point of view; one that he may have to invent for himself. I say sacrificed himself because he most likely will get nothing from it, because the truth may lie in another direction, perhaps even the fashionable one.

But, if my own experience is any guide, the sacrifice is really not great because if the peculiar viewpoint taken is truly experimentally equivalent to the usual in the realm of the known there is always a range of applications and problems in this realm for which the special viewpoint gives one a special power and clarity of thought, which is valuable in itself. Furthermore, in the search for new laws, you always have the psychological excitement of feeling that possible nobody has yet thought of the crazy possibility you are looking at right now.

So what happened to the old theory that I fell in love with as a youth? Well, I would say it's become an old lady, that has very little attractive left in her and the young today will not have their hearts pound when they look at her anymore. But, we can say the best we can for any old woman, that she has been a very good mother and she has given birth to some very good children. And, I thank the Swedish Academy of Sciences for complimenting one of them. Thank you.

From *Nobel Lectures, Physics 1963-1970*, Elsevier Publishing Company, Amsterdam, 1972

History: ***Light Quanta***

- _______________(550 BC) - light comes from luminous bodies in very fine particles
- ________________ (450 BC) - light is made of high-speed waves of some sort

- ______________ (______BC) - light is made of streamers emitted by the eye
- ______________ (300 BC) - same as Plato
- ______________ (1700 AD) - light is made of a stream of corpuscles (although he saw 'Newton's Rings' of interference)
- ______________ (1700 AD) - light is made of waves
- ______________ (1801) - light is made of waves - famous double slit experiment
- ______________ (1862) - light is made of oscillating electromagnetic fields
- ______________ (1887) - light (actually radio) is made of electromagnetic waves
- ______________ (1905) - light is made of tiny packets of energy (Nobel prize winning paper on photoelectric effect - he also published in that same year: doctoral thesis on sugar molecule size and Avogadro's number, theory of Brownian motion, theory of Special Relativity, and a paper on e=mc2.
- **At this point in history … we think light is both wave and particle … we call this the Quantum Theory**

Quantum Physics – Part II

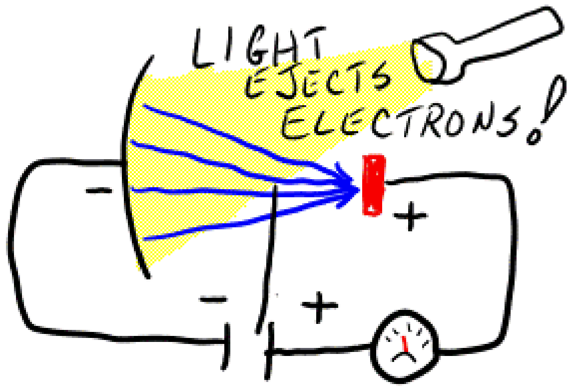
Concept: ***Quantum Theory***

- Birth of ______________ - 1897: discovery of electron and radioactivity
- Max ______________ - (Nobel Prize) 1900: bodies emit energy bundles called quanta (plural of quantum)
- Quantum ______________: how things *move* in the microworld
- Quantum ______________: laws of the microworld
- Planck's Constant (h = 6.6 x 10-34 Joule seconds): says that there is a smallest amount of energy (E) that light (of frequency f) can have - it is ______________ - this means that the universe is *granular* in some respect

$$E = h \times f$$

Quantum Experiment #1:
Photoelectric Effect

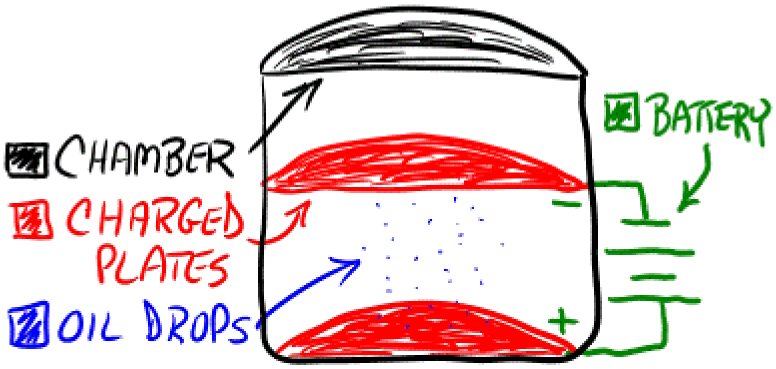
- Light Ejects ______________ ('Photoelectric Effect'): Einstein (Nobel Prize 1905)
    - But they start ejecting immediately - even in weak light!
    - They eject better with violet and ultraviolet than with red and infrared.
    - More light ejected more electrons - but not higher energy electrons.


LIGHT
EJECTS
ELECTRONS!

Quantum Experiment #2:
Millikan Oil Drop

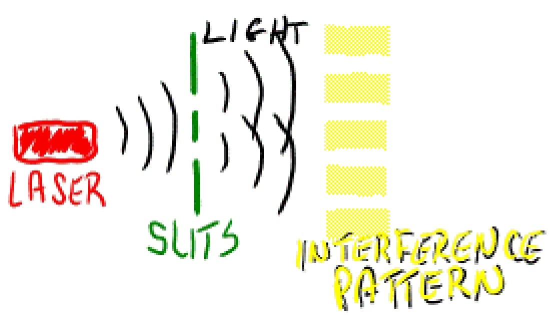
- Electric Charge is a Quantum of One ________________: Millikan (Nobel Prize 1926)
  - He sprayed tiny, charged oil drops.
  - He could keep them from falling with an electrical plate.
  - All charges needed were multiples of 1.6 x 10-19 C,

  the charge of one electron!



Quantum Experiment #3:
Young's Double Slit

- Even single ________________ make ________________ patterns like waves: Thomas Young (1801)
  - He sent beams of light through two slits: interference pattern.
  - He sent single photon through one of two slits: interference pattern.
  - He sent single photon through one slit: no interference pattern.
  - The big question is … "How does the single photon going through one of the two slits 'know' to go into an interference pattern?" The best answer so far is … "The wave nature of light is in every single photon!"



Quantum Experiment #4:
de Broglie's Wavelength

- Everything has a ________________: Louis de Broglie (1924)
    - Light has a wavelength; but so do electrons, people and planets!
    - The smaller the momentum, the larger the ________________.

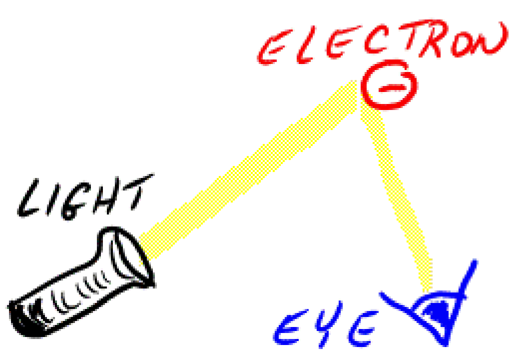
$$\text{WAVELENGTH} = \frac{h}{\text{MOMENTUM}} \quad \text{or} \quad \lambda = \frac{h}{p}$$

Quantum Experiment #5:
Heisenberg's Uncertainty Principle

- You ________________ know both momentum and position of something with certainty: Werner Heisenberg (1927)
    - 2 ways to explain Heisenberg
        1. To know things you must ask; and this involves ________________ the very thing you wish to know.
           ("Let's find out if she is sleeping; I'll tap her on the shoulder.")
        2. Since the wavelength and frequency of a wave are inversely proportional; if one gets smaller the other gets larger.

$$\lambda = 1/f$$

("Let's 'see' that electron with a tiny wavelength that is not so broad. Whoops, it had so much energy from its high frequency, that it really changed the electron's energy. I know, I'll shine a low energy (low frequency) light on it. Whoops, the light bounced back with such a broad wavelength that it is only letting me know the general position of the electron.")



Concept: ***Complementarity***

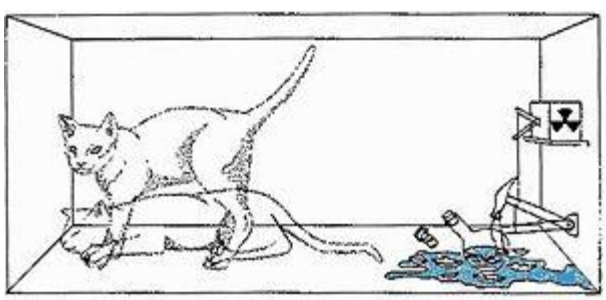
- Niels ________________ (Nobel Prize 1922 for model of atom with Rutherford):
  - Light and in fact all matter act like *waves* in certain ways and like *particles* in other ways.
  - This is a dualism.
  - Bohr said there is a wholeness in the understanding of light - somehow it is both.
  - It depends on your experiment.
  - If your experiment looks for individual energies and momenta, you see particles.
    If your experiment looks for spatial distribution of energy, you see waves.
  - He called this dualism, Complementarity - not a compromise - not somewhere between particles and waves - Light, Energy, and Matter are wholes that include both particle and wave natures.
  - When Bohr was knighted (1947) for his physics, he chose the yin-yang symbol for his coat of arms.

Concept: ***Schrodinger's Wave Equation***

- Erwin Schrodinger (Nobel Prize 1933):

Schrodinger's ______________ … in his own words …

"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts."



Schrödinger's Cat: A cat, along with a flask containing a poison, is placed in a sealed box shielded against environmentally induced quantum decoherence. The flask is shattered, releasing the poison, if a Geiger counter detects radiation. Quantum mechanics seems to suggest that after a while the cat is *simultaneously* alive and dead, in a quantum superposition of coexisting alive and dead states. Yet when we look in the box we expect to see the cat *either* alive *or* dead, not in a mixture of alive *and* dead.

- Schrodinger's Wave Equation is to Quantum Physics what Newton's Second Law of Motion (f = ma) is to Classical Physics.
- Basically, it says that matter is made of waves that cannot be said to be 100% sure to be in any one place. Their location is a probability. For example, Schrodinger's Wave Equation would tell you that the electron of the Hydrogen atom would be in a certain position with a 40% probability. It would never say that there is no chance (0%) or definite certainty (100%) of that electron being anywhere.
- The equation is quite complex - but for fun - here it is.

$$\Psi(x,t) = \sum_n C_n \, u_n(x) \exp\left(-iE_n t/\hbar\right)$$