Time Examined Class Notes – March 7, 2019 (md)

1. In many physics curricula, we offer a course called *Modern Physics*, which really emphasizes the "non-classical" physics developed in the first half of the 20th century. The need to go beyond classical ideas was apparent when studies ventured into realms beyond everyday experience.

You have already seen one of those realms – *the very fast*. If we consider the motion of things at speeds near the speed of light as Einstein did, we have to adapt our notions of simultaneity, space, and time.

The other realm of concern to us is *the very small.* When we look at atoms and things smaller than that, we observe non-classical behaviors that call into question whether reality is a continuum or split up into discrete elements, what level of certainty we can have about phenomena, and even call into question the notion of causality.

2. Our excursion into the land of the *quantum* starts around 1900 with a seemingly obscure problem – radiation emitted by heated bodies. A lot was known about this phenomenon. When you heat something up:

- a wide range of frequencies of electromagnetic energy is emitted (UV, IR, light),
- the general shape of the Intensity *vs.* frequency spectrum is known, and
- the peak of the Intensity occurs at a frequency proportional to the temperature.

But the standard theories of electromagnetic emission did not predict any of this.

3. The person that cracked the problem was Max Planck (1900), but he did it by making an unnerving assumption. He suggested that the EM radiation we see is emitted by the oscillating atoms of the material (non-controversial), but that an oscillator with frequency f could only emit EM radiation with energy (non-classical):

$E = h\,f$ or $2\,h\,f$ or $3\,h\,f, \ldots$ with h being a constant he determined from data.

So emission of EM radiation is a *quantized* process, having only discrete values.

4. In 1905, Einstein published a paper taking this quantum idea one step further. He theorized that the *EM radiation itself* was quantized. That is, light and other EM radiation came in little packets of energy (which we now call *photons*), with $E = h\,f$. Somehow, light was both a wave and a particle.

5. Around 1911, Niels Bohr used a quantum assumption to solve one of the great mysteries of atomic physics: discrete line spectra.

People knew that an atom has a small positively charged nucleus, which is surrounded by a cloud of orbiting negatively charged electrons. The puzzle was that classical EM theory predicted that such an orbiting electron would continually radiate its energy, eventually crashing into the nucleus. That leads to questions, like,

- What keeps the orbiting electron from radiating?
- Why is that the radiation we *do* see from an atom is only at specific frequencies?

Bohr theorized that the electrons had specific stable orbits in which they did not radiate, and he came up with theory of what those orbits should be. Then when an electron transitions from one energy level to another, it absorbs or emits a photon whose energy is the energy difference between the two electron states. That is, if the electron could be in a lower energy state E_1 or a higher energy state E_2, then:

Emission: Electron drops from E_2 to E_1, and a photon with $E_\gamma = E_2 - E_1$ is emitted.

Absorption: Electron absorbs a photon with $E_\gamma = E_2 - E_1$, and it jumps from E_1 to E_2.

6. The details of Bohr's model turned out to be only narrowly applicable to providing an explanation of the Hydrogen atom's radiation, but the general idea has proved almost universally true for systems like molecules, atoms, and smaller things:

- Quantum systems can have only specific stable states,
- A system undergoing a change transitions from one stable state to another,
- The change often involves the absorption or emission of another particle, and
- The energy of the absorbed or emitted particle is given by $\Delta E = E_2 - E_1$.

7. Louis de Broglie (1924) theorized that just as a light is a wave that manifests particle properties, particles like electrons must also manifest wave properties. This idea can be used to explain Bohr's results, and it suggested that particles should scatter like waves. This was confirmed experimentally by Davisson & Germer (1927), showing that electrons scatter off crystals, exhibiting interference effect just like light waves do.

8. *Interference* is the crucial character of waves, so let me explain with a sound wave.

If a speaker makes a sound wave, it gets molecule of air near it vibrating as the speaker vibrates back and forth. This sets up a chain reaction of air molecules hitting adjacent air molecules, which hit the next adjacent air molecules, … Eventually, the air resting against your ear drum gets vibrated in and out, and that vibration sets your ear drum moving, which begins your hearing process.

But what if two waves from two different sources hit your ear drum at the same time?

- If they push your ear drum in and out in sync, you hear a sound twice as loud,
- If one pushes the ear drum in while the other is pulling it out, they can cancel.

These are *constructive interference* and *destructive interference*, respectively.

9. Possibly because we experience them routinely, it is not hard to imagine sound or light waves undergoing interference, but what might it mean for particles? How could two electron beams "cancel each other out"? This is one of the fundamental mysteries of quantum behavior, dubbed the *wave-particle duality*. Despite its counter-intuitive nature, we are very sure that all very small systems behave this way.

10. One consequence of this is that we can rarely say <u>what will happen</u>, instead, we are limited to giving <u>probabilities of various outcomes</u>. The probabilistic nature of subatomic phenomena is inescapable. It isn't just that we don't happen to know which of the possible outcomes occurs, there is no way of knowing in advance which outcome will occur, even hypothetically.

My favorite example of this is when a system undergoes a transition, like emitting a photon, or a radioactive nucleus undergoing α- or β-decay. Suppose that I have 100 identical nuclei and the half-life of their decay is 20 ms. I am very confident that after 20 ms, about 50 of the nuclei will have decayed and 50 will not have decayed. But, *there is no difference between the nuclei that decayed and the ones that did not.*