Quantum Mechanics: Motivations

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1 General Comments

- Quantum Mechanics describes atomic and subatomic length-scale systems and phenomena
- Classical mechanics/physics (describes "large" systems; Newtonian mechanics; **deterministic**
- By end of 19^{th} century, physics treated **matter** and **radiation** separately
- Matter: Newtonian mechanics; Radiation: electromagnetic theory (unification of phenomena related to electricity, magnetism, and optics; Maxwell's equations)
- Electromagnetic theory of **radiation** confirmed/validated experimentally by discovery of Hertzian waves
- Finally, *interactions between matter and radiation* explained by Lorentz force

  $$\mathbf{F} = q\mathbf{E} + q(\mathbf{v}\ \mathbf{x}\ \mathbf{B})$$

  force on charge, q, due to E and B fields

2 Challenges to Classical Physics

- quantum mechanics and relativity addressed deficiencies of classical mechanics/physics at scales of speed and lengths (relativity dealing with matter at speeds on the order of speed of light; quantum mechanics dealing with matter on the length scales of atoms and electrons)
- Classical physics is a limit of both cases (we will see the classical limit of quantum mechanics in upcoming lectures); this is a satisfying aspect of quantum theory (has the right limiting behavior)

- Quantum theory is just that– a **theory**. helps us explain and predict phenomena. remains intact until it breaks and has to be fixed/revised/reformulated (no indication of this)
- challenge: unification of quantum and relativity theories
- Most atomic and molecular phenomena (until one hits heavier nuclei) are treated well by non-relativistic quantum mechanics

3 Elementary Ideas of Quantum Mechanics

- Energy is quantized

  blackbody radiation, photoelectric effect, emission spectra for gases

  Photoelectric Effect: emission of bound electrons from metals (Einstein)

  $$KE_{electron} = \beta\nu - \phi \tag{1}$$

  (kinetic energy of emitted electrons is linearly proportional to frequency of incident photons; threshold frequency required before electrons emitted; quantization of photons)

  Planck proposed quantization to explain blackbody radiation; Einstein invoked particle nature of light (photons) and quantization of photon energy. Compton demonstrated photons in 1924 (Compton effect)

- Wave-particle duality of matter

4 Wave-Particle Duality; Young's Double Slit Experiment; Davisson-Germer Experiment; Compton Scattering

Here we consider a classic experiment (originally related to light and its behavior) but later shown for electrons (Davisson and Germer; scattered electrons from Nickel surface, 1927). This forces us to consider the wave-particle duality of matter. More fundamentally, it leads us to the notions of spectral decomposition (linear superposition of states) as well as implications of **the measurement process** on quantum systems. These ideas are at the heart of quantum mechanics and the operational (vis-a-vis, mathematical) language of the field.

5 The experiment

Consider the experimental setup:

- monochromatic light (or electrons of given energy/wavelength, of course with different experimental setup) generated and emitted from source, S
- construct experiment to only direct **single** photon or electron at a time; thus no interactions
- Screen with one or two slits (of the dimensions of Angstroms)
- observation screen (photographic plate, i.e.)
- Single slit open (either one): diffraction pattern
- Both slits open: interference pattern
- behavior of intensity: $I(x) \neq I_1(x) + I_2(x)$
- pattern shows dark and bright fringes (reminiscent of **waves** interfering)
- However, we have said that photons and electrons are arriving as particles.
- Further thoughts

  If the experiment is performed for a long time, with single photon/electrons arriving at the detector screen, interference patterns are observed

  If the experiment is performed for a short time (enough to receive a "few" electrons), the interference patterns are not apparent, but the individual "impacts" are notable (note however, that if this collection were allowed to progress for "long" time, the individual impacts, though seemingly random, would build up into a continuous pattern displaying interference (bright/dark) fringes. **Photons/electrons as they arrive, build up the interference pattern**
- Thus, a purely particle or wave description is not sufficient to represent the particle

- Consider: we are sending in one particle at a time (photon/electron); interference occurs due to the constructive/destructive interference between 2 waves. So how can a single particle give rise to interference patterns?

- In the preceding discussion, we have not made any effort to determine through which slit the particle passes. If we were to place a detector at either slit, we would see that the interference pattern would disappear. Also, with detectors at both slits, we would see that each particle arriving at the screen would show up as a single event (and it turns out that one-half go to each slit on average).

  Thus, by obtaining information on where the particle goes, we lose the diffraction pattern. It seems that the presence of interference pattern depends on whether we perturb the system by measuring it in some way.

- Planck-Einstein Relations:

$$\begin{aligned} E &= h\nu = \hbar\omega \\ \mathbf{p} &= \hbar\mathbf{k} \end{aligned}$$

- fundamental relations:

$$\begin{aligned} \omega &= 2\pi\nu \\ |\mathbf{k}| &= \frac{2\pi}{\lambda} \end{aligned}$$

6 Final Remarks

- Particles are represented as waves (and vice-versa)
- The description of a particle entails non-determinism
- This non-determinism is represented through a **superposition** description
- $$\psi_{particle} = \psi_1 + \psi_2 + \psi_3 + \cdots$$
- The individual ψ are **possible states** (i.e., left slit, right slit, no slit)
- By taking a measurement, we **pick out** one of the states; thus, the original state has been changed due to our measurement!
- It turns out, measurements in real life are analogous to mathematical operators (recall from linear algebra); the properties measured are eigenvalues.