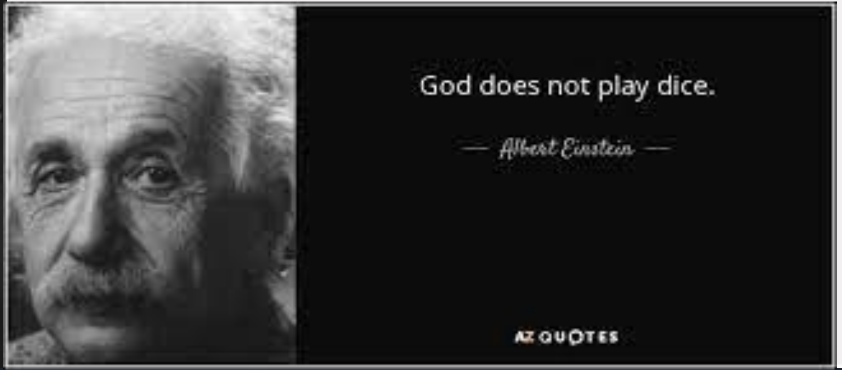

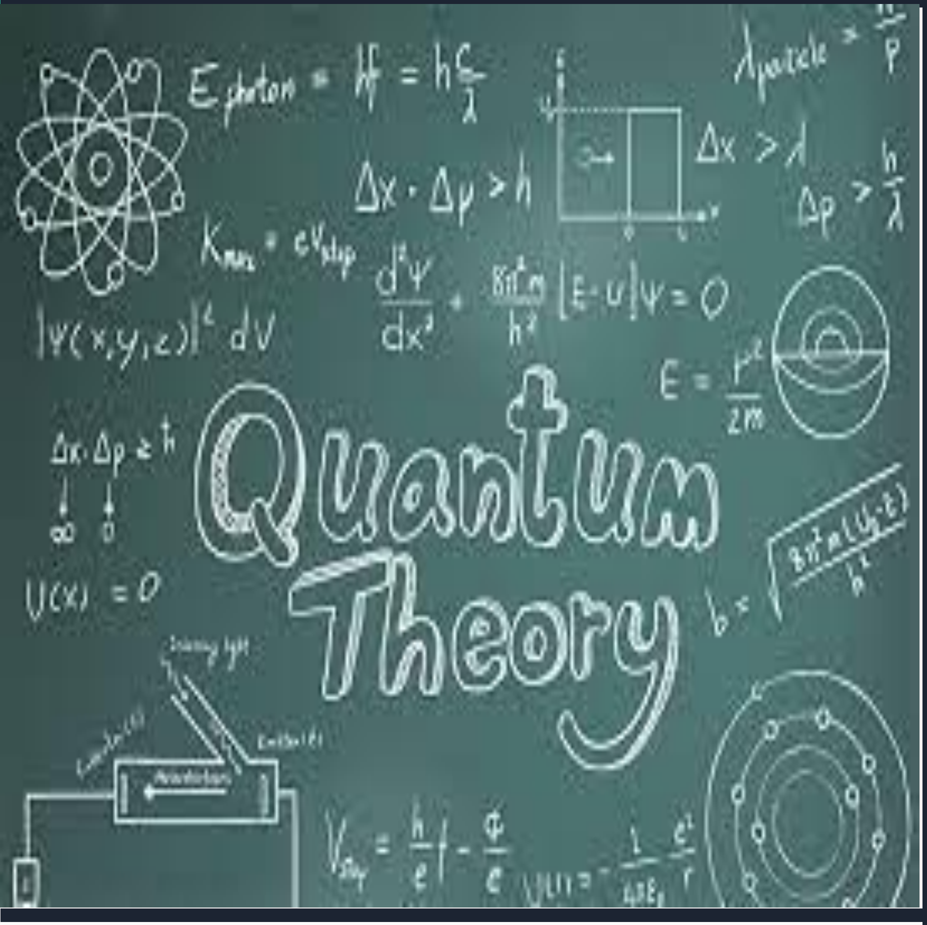

QUANTUM PHYSICS: BACKGROUNDS & FOUNDATIONS

Zulkaida Akbar

9/15/2022

Salam Kenal

- Asal Purwokerto
- TK – SD - SMP- SMA di Purwokerto
- S1 di Fisika ITB (2003 – 2009)
- Mengajar di STKIP Surya (2011 – 2013)
- S2 di Florida State University (2013 – 2015)
- S3 di Florida State University (2013 – 2018)
- Research Associate di University of Virginia (2018 – Sekarang)

- Bidang riset: Fisika Nuklir & Partikel
- Tempat riset: Fermi National Accelerator Laboratory (Fermilab) dan Thomas Jefferson National Laboratory (JLab)
- Fermilab dan Jlab adalah laboratorium Nuklir dan Partikel dibawah Department of Energy, USA

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OUTLINE

- Classical-Physics Foundations
- Crack in Classical Physics
- Quantum solutions
- Quantum postulates & foundation
- General applications
- Summary & Outlook
- Philosophical discussions

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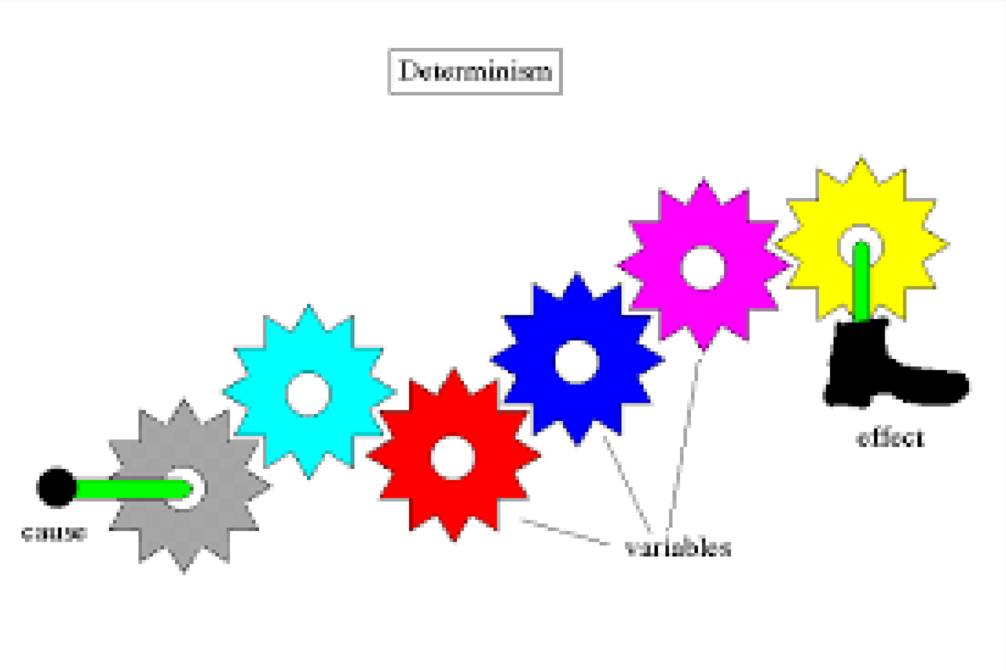
Classical-Physics Foundations

- Classical physics (Newtonian physics) work for macroscopic or big objects with low speed (far lower than the speed of light)
- Deterministic: Universe is like a giant clock & fully mechanistic. If we know the initial condition of an object, we understand the applied force, we can determine with a great precision the whole trajectory and the future of the object



Applied force

Initial position & velocity

Newton law

$x(t), v(t), \ldots$

Quiz: If nature is deterministic then why we learn probability at school?

The probability of getting “head” when tossing a coin is $^1/_2$

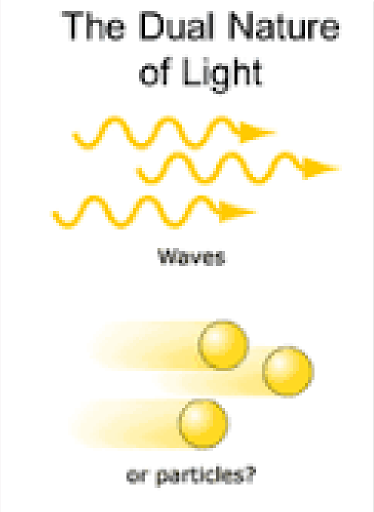
The probability of getting “1” when rolling a dice is $^1/_6$

Answer:

- Nature is deterministic
- The probabilistic feature is due to our limitation in accessing the full information from nature
- Therefore, if we know the exact and complete force distribution of the hand who toss the coin, we know exactly the viscosity and density of air, the wind, etc then in principle we could predict which side of coin will land (head or tail)
- Same story with the dice. If we know all information, then in principle we could predict which number will land
- So, the probabilistic feature arise from our ignorance or the incomplete information that we have

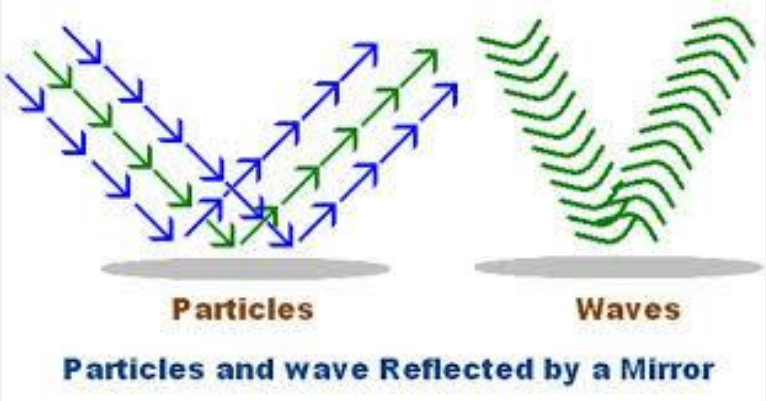
Classical-Physics Foundations

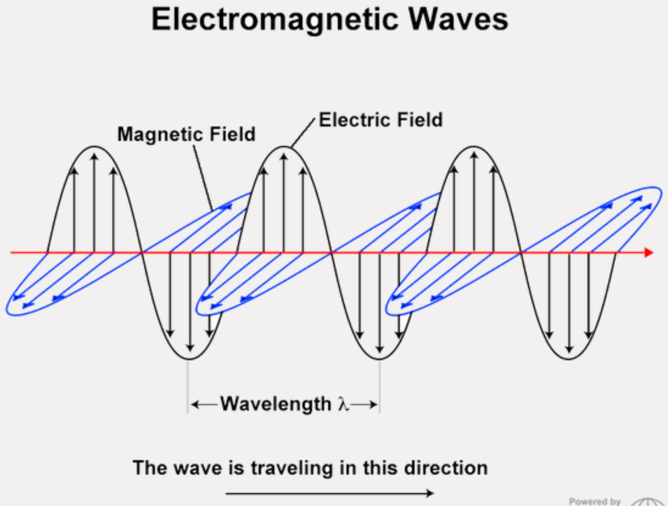
- Distinct features of “particle” versus “wave”
- Particle: clear position (Lumping, cluster), clear momentum, NOT interference
- Wave: Position is not clear (spread), interference



Property	Wave model	Particle model
Reflection	✓	✓
Refraction	✓	✓
Polarization	✓	✗
Diffraction	✓	✗
Interference	✓	✗
Photoelectric effect	✗	✓
Compton effect	✗	✓

Particles	**Waves**
Mass	Frequency
Size	Wavelength
Kinetic Energy	Amplitude
Momentum	





Bullets (particle) versus wave in a double-slit experiment

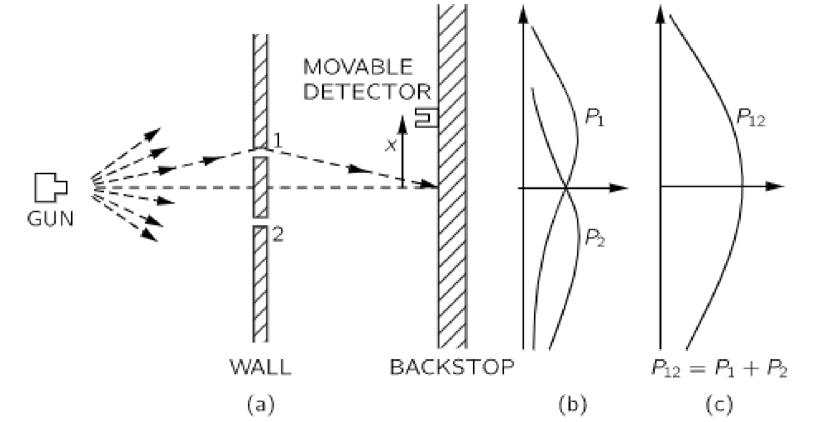
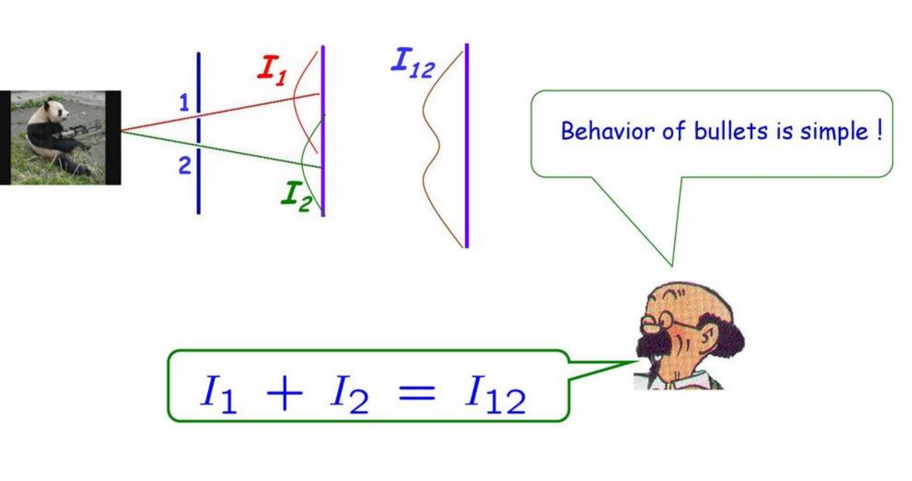


Fig. 1–1. Interference experiment with bullets.



Particles don't have interference

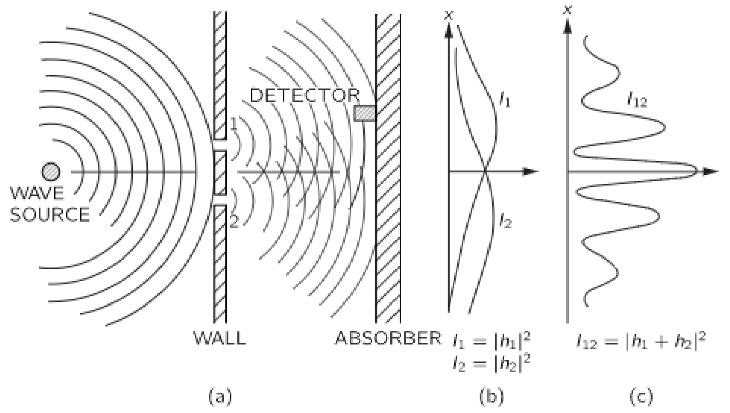
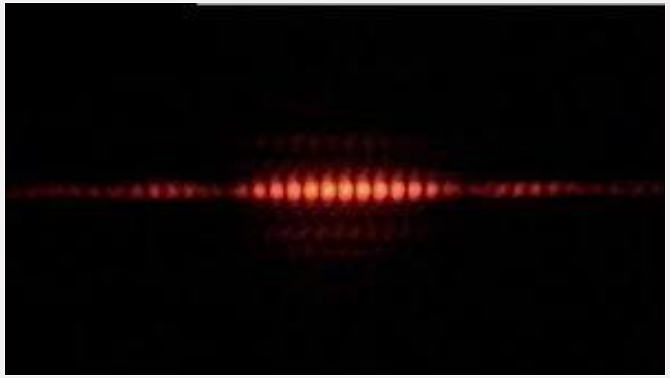


Fig. 1–2. Interference experiment with water waves.



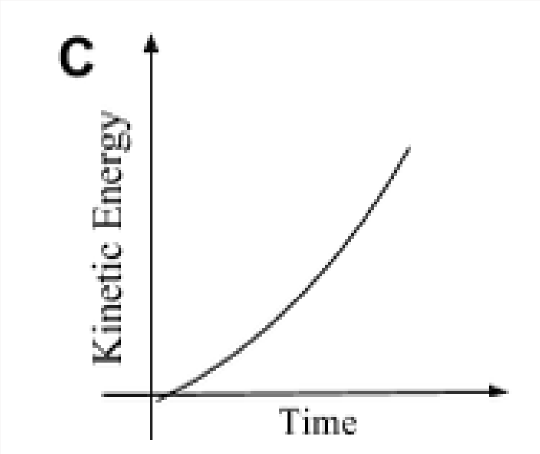
$$|h_1 + h_2|^2 = |h_1|^2 + |h_2|^2 + 2|h_1||h_2| \cos \delta,$$

$$I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta.$$

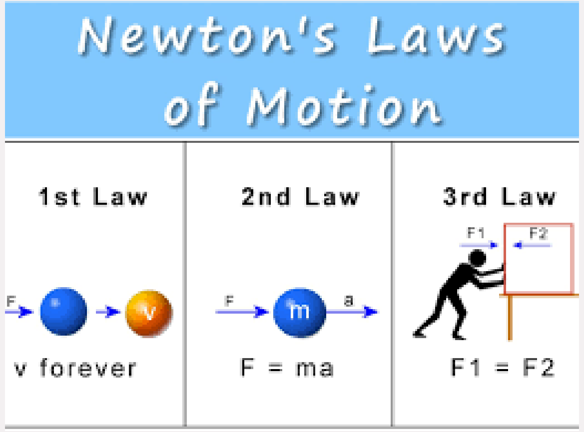
Waves have interference

Classical-Physics Foundations

- Energy is continuous
- Energy of a particle or wave could take any values



- Govern by newton law (for mechanic) and maxwell equations (for electromagnetism)



Maxwell's Equations — Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}$$

Maxwell's Equations — Integral form

$$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$$

$$\oint \vec{E} \cdot d\vec{l} = \boxed{-\int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{a}}$$

$$\oint \vec{B} \cdot d\vec{a} = 0$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \boxed{\mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}}$$

- Objectivism: Observer and Object are separated. Measurement without altering the system

Classical-Physics Foundations: A Brief Summary

- Classical physics (Newtonian physics) work for macroscopic or big objects with low speed (far lower than the speed of light)
- Deterministic: Universe is like a giant clock & fully mechanistic. If we know the initial condition of an object, we understand the applied force, we can determine with a great precision the whole trajectory and the future of the object
- Distinct features of “particle” versus “wave”
- Energy is continuous
- Govern by newton law (for mechanic) and maxwell equations (for electromagnetism)
- Objectivism

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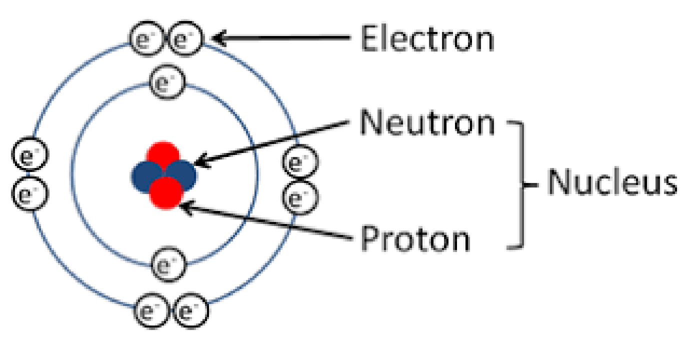
Crack in Classical Physics: Atomic structure

- Classical atomic structure:

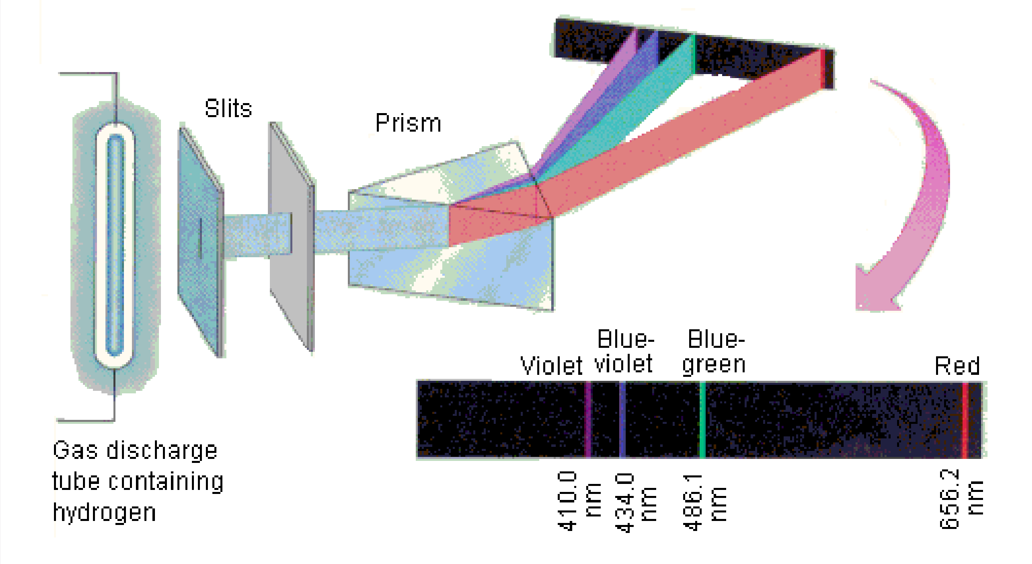


- Electrons are orbiting nucleus
- It means electrons have acceleration (centripetal acceleration)
- But, according to Maxwell theory, accelerated charge produce electromagnetic wave or radiate energy
- Moving electron -> current -> Magnetic field
- Accelerated electron -> changing Magnetic field -> changing electric field -> changing magnetic field -> ⋯ (EM waves)
- If orbiting electron radiate energy (in the form of EM waves), electron should lose its energy
- Electron should gradually collapse to nucleus due to loosing its energy
- Atom will collapse and not stable

Classical physics failed to explain why atoms are stable

Crack in Classical Physics: Hydrogen emission spectrum

- When an electric current is passed through a glass tube that contains hydrogen gas at low pressure the tube gives off blue light. When this light is passed through a prism, some narrow bands of bright light are observed against a black background



Wavelength	Color
656.2	red
486.1	blue-green
434.0	blue-violet
410.1	violet

$$\frac{1}{\lambda} = R_H\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$

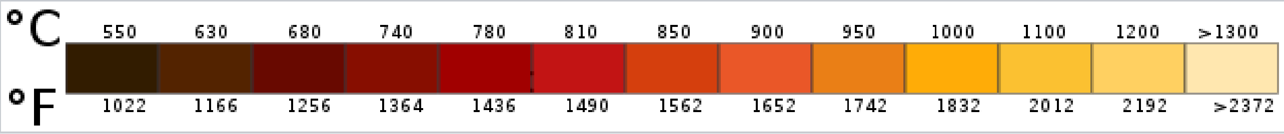
Classical physics failed to explain Hydrogen emission spectrum

Crack in Classical Physics: Blackbody radiation

- Hot objects emit visible light (EM radiation) that depend on the temperature

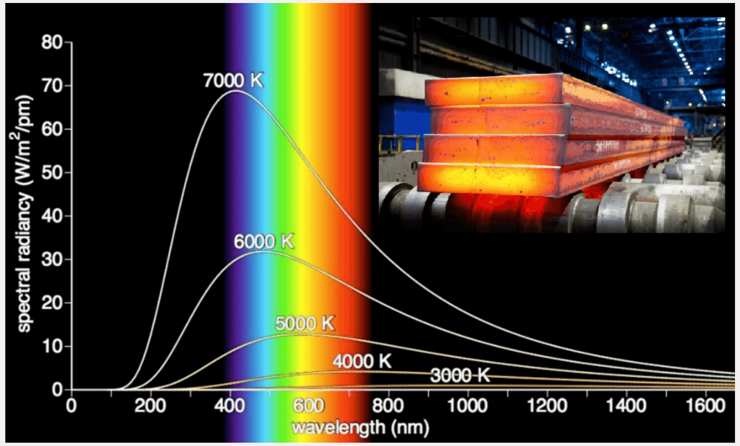
The temperature of a Pāhoehoe lava flow can be estimated by observing its color. The result agrees well with other measurements of temperatures of lava flows at about 1,000 to 1,200 °C (1,830 to 2,190 °F).

Blacksmiths judge workpiece temperatures by the colour of the glow.[9]



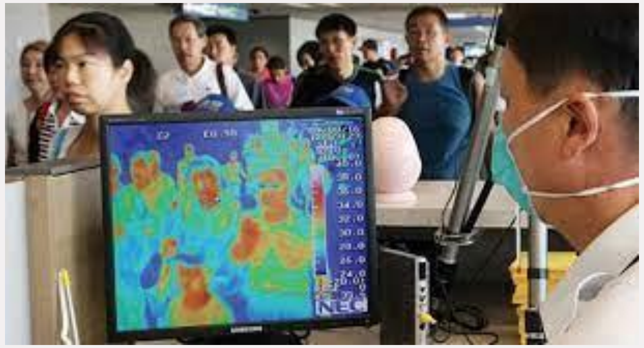
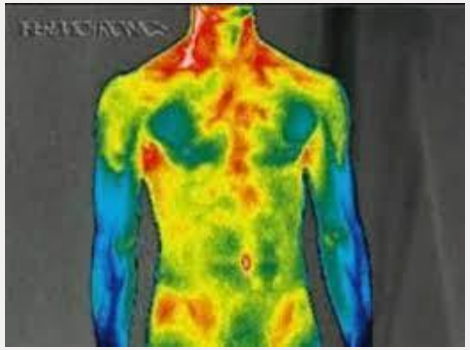
This blacksmith's colourchart stops at the melting temperature of steel.

- Essentially, all objects emit electromagnetic wave (radiation) in ALL frequency. But the intensity for each frequency depend on the Temperature $I(\lambda, T)$. We see hot objects emit visible light since the most intense radiation are in the area of visible light spectrum

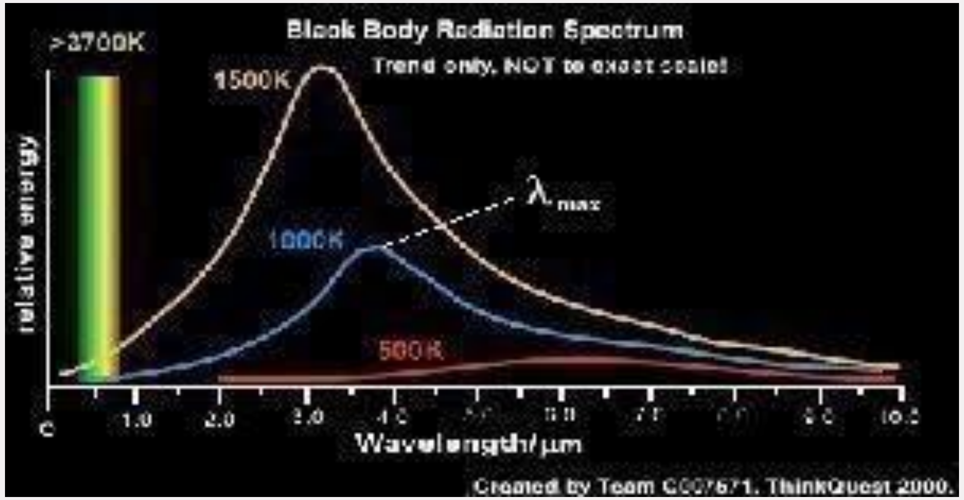


Crack in Classical Physics: Blackbody radiation

- At room temperature, the most intense radiation are not in the visible-light spectrum (that's why we are not glowing) but in the infrared spectrum. Hence, we need special device to see the radiation

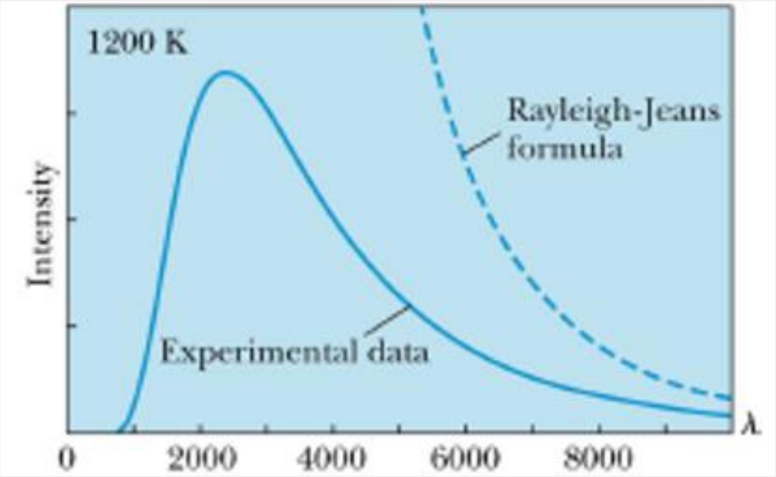
- The most intense wavelength as a function of temperature for an object follow Wien's law

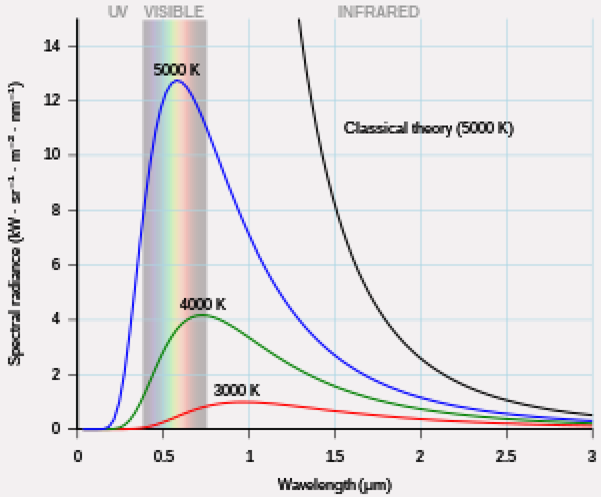


$$\boxed{\lambda_{max} T = 2.898 \times 10^{-3}\ \mathrm{m \cdot K}}$$

Crack in Classical Physics: Blackbody radiation

- Rayleigh & Jeans, using classical electromagnetism & thermodynamics, tried to explain the curve shape but they failed. Their prediction leads to “Ultraviolet Catastrophe”

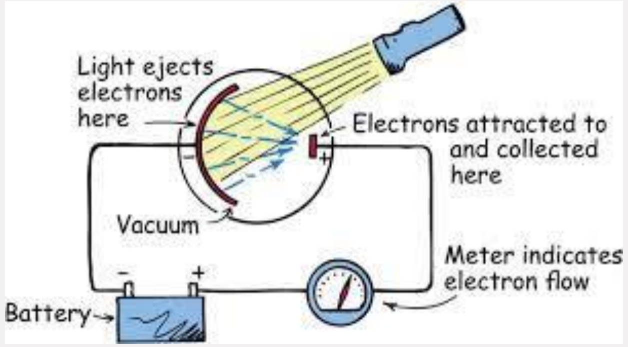




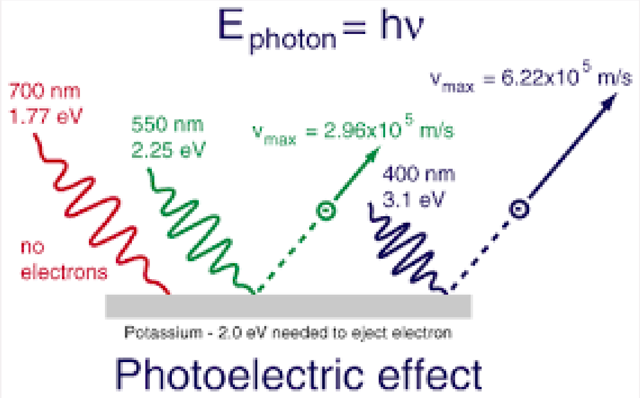
Classical physics failed to explain the curve shape of the blackbody radiation

Crack in Classical Physics: Photoelectric effect

- The **photoelectric effect** is the emission of electrons when electromagnetic radiation, such as light, hits a material. Electrons emitted in this manner are called photoelectrons.

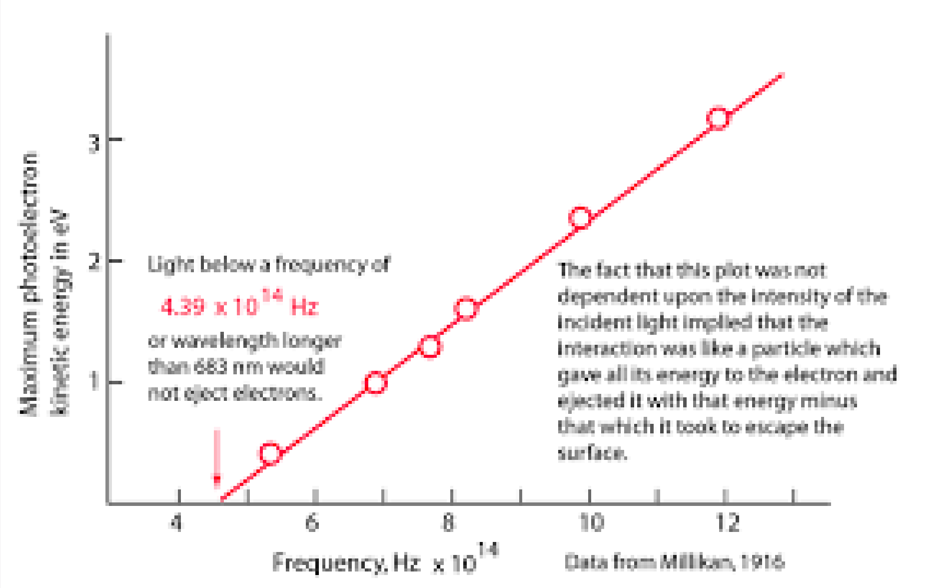


- The photoelectric effect only happen after some threshold of the light frequency. Hence, some light could not produce photoelectrons even though very bright/intense (1000 Watt) but other lights could produce photoelectrons even thought very dim (0.001 Watt)



Crack in Classical Physics: Photoelectric effect

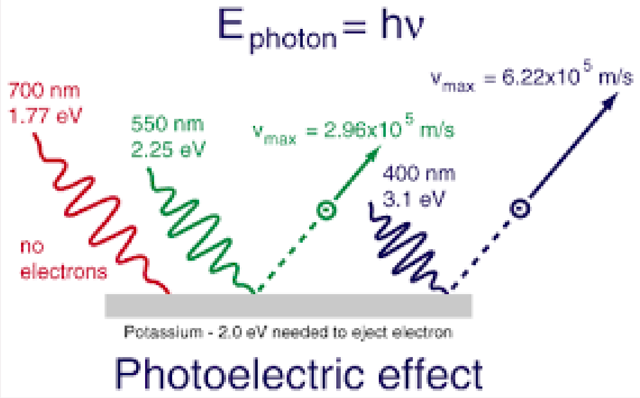
- The production of photoelectrons are instantaneous, and the maximum kinetic energy of the electrons are dependent on the frequency/wavelength of light who hit the metal



Crack in Classical Physics: Photoelectric effect

The classical theory of wave failed to explain the photoelectric effect:

- As a wave, the light energy depends on the intensity. Therefore, a very bright red light (1 Million Watt) should eject more electrons, but no electron is ejected from the metal



- The ejection of the photoelectrons is instantaneous. The theory predict that the metal need time to absorb and collect energy from the wave before ejecting any electron

Classical wave theory (light as wave) failed to explain photoelectric effect

Crack in Classical Physics: Wave-Particle dualism

- As a particle, we expect that the electron follow the same pattern with bullet when passing double slit apparatus. But the experiment shows that electron follow wave pattern instead

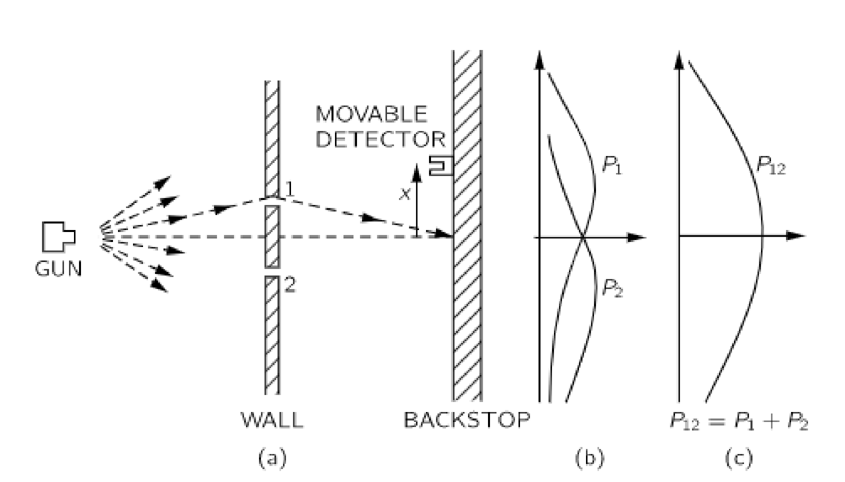


Fig. 1–1. Interference experiment with bullets.

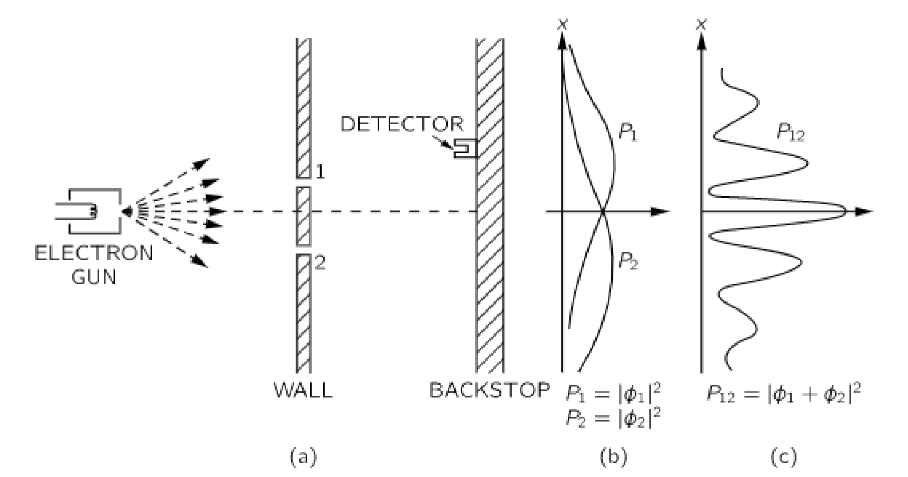
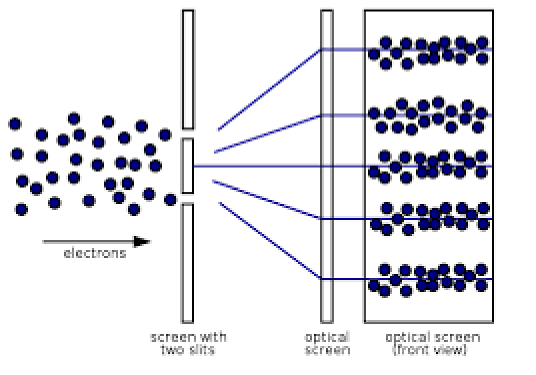
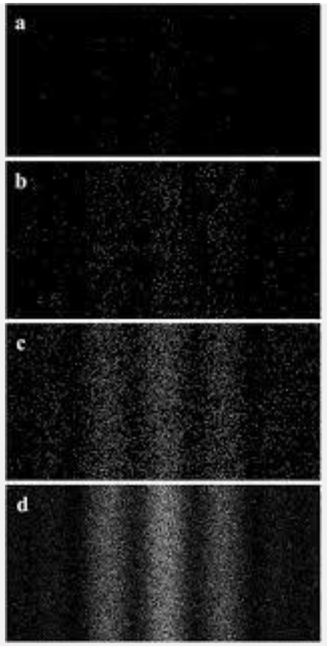


Fig. 1–3. Interference experiment with electrons.





Expected

Reality

Classical physics failed to explain why electron behave like a wave

Crack in particle physics: A Brief Summary

Classical physics failed in explaining:
- Why atoms are stable
- The origin of the Hydrogen emission spectrum
- The shape of the blackbody radiation curve
- Photoelectric effect
- Why electron behave like a wave

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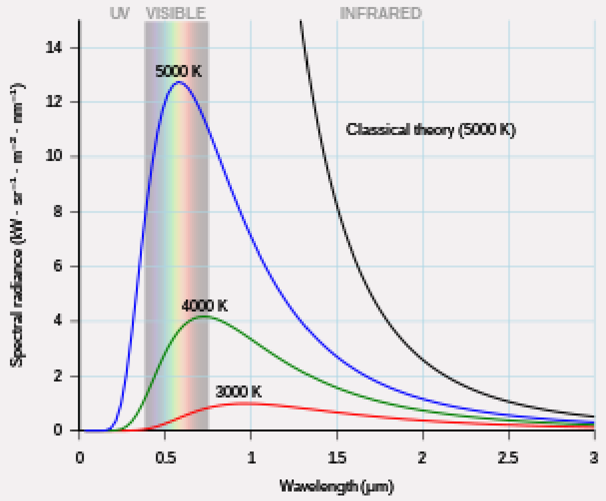
Quantum solutions: Blackbody radiation

- Max Planck solve the blackbody radiation problem by stating that the **radiation energy is not continuous but consist of chunk or discrete package (quanta)**



- Planck assumed that the radiation in the cavity was emitted (and absorbed) by some sort of "oscillators" contained in the walls. He used Boltzman's statistical methods to arrive at the following formula:

$$\boxed{\mathcal{I}(\lambda,T)=\frac{2\pi c^2 h}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}}$$

Planck's radiation law

- Planck made two modifications to the classical theory:
  1) The oscillators (of electromagnetic origin) can only have certain discrete energies determined by $E_n = nh\nu$, where n is an integer, ν is the frequency, and h is called Planck's constant.

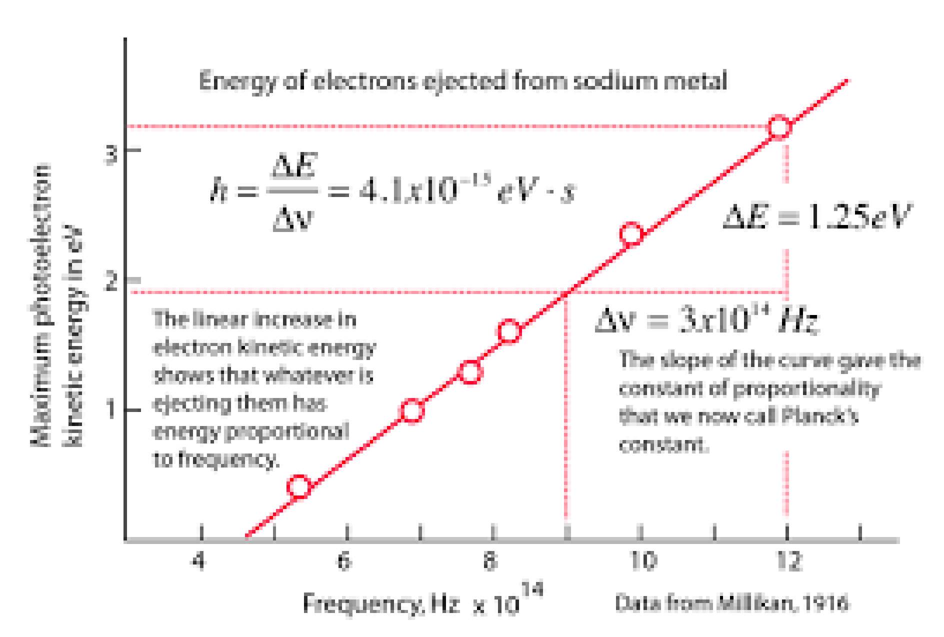
$$h = 6.6261 \times 10^{-34}\ \text{J·s.}$$

  2) The oscillators can absorb or emit energy in discrete multiples of the fundamental quantum of energy given by

$$\Delta E = h\nu$$

Quantum solutions: Photoelectric effect

- Einstein solved the photoelectric effect by stating that **light consist of localized particles called photon** which carry discrete energy proportional to the frequency



"According to the assumption to be contemplated here, when a light ray is spreading from a point, the energy is not distributed continuously over ever-increasing spaces, but consists of a finite number of energy quanta that are localized in points in space, move without dividing, and can be absorbed or generated only as a whole."

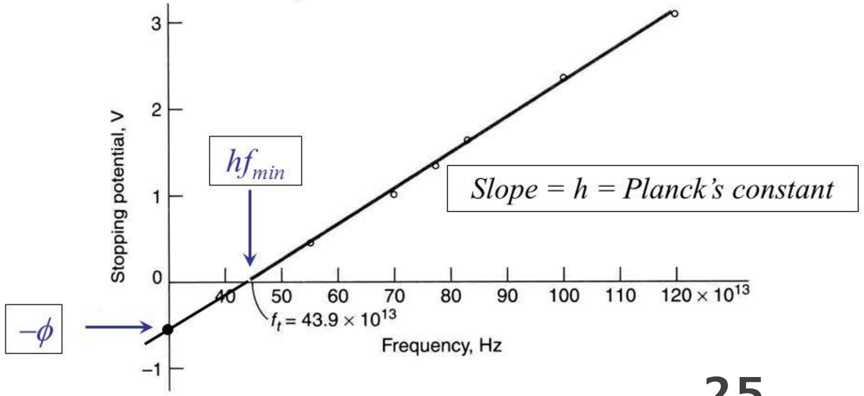
$$E = hf$$

- Each photo electron gets the energy from a single photon
- Energy of electrons are same for brighter and dimer light

Photoelectric Effect: V_{stop} vs. Frequency

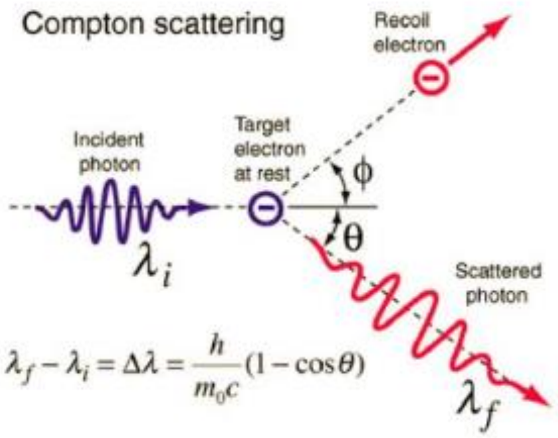
$$\boxed{eV_{stop} = hf - \phi}$$

$$V_{stop} = 0 \Rightarrow hf_{min} = \phi$$



Quantum solutions: Compton scattering -> Prove of Einstein theorem

- When x-rays are scattered by atoms their λ increase.
- Incoming photon scatters off an electron that is initially at rest
- Collision between two particles
  - Energy-momentum must both be conserved simultaneously

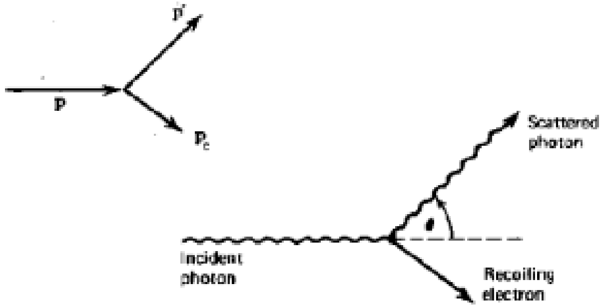


$$\lambda_f - \lambda_i = \frac{h}{m_e c^2}(1-\cos\theta)$$

Light consist of particles called photons

Experimental results

Efek Compton adalah gejala yang timbul jika radiasi (sinar x) berinteraksi dengan partikel (elektron). Foton sinar x bersifat sebagai partikel dengan momentum $p = \frac{hf}{c} = \frac{h}{\lambda}$. Skema efek Compton diberikan pada gambar 1.3. Efek Compton dapat dijelaskan meng-



Gambar 1.3 Skema efek Compton. Foton datang dengan momentum p dan menumbuk elektron yang diam. Lalu foton terhambur dengan momentum p' dan elektron terhambur dengan momentum p_e. Sudut hamburan foton θ dihitung terhadap arah datangnya. (Gambar diambil dari [1])

gunakan konsep momentum dan tumbukan. Tumbukan dianggap bersifat lenting sempurna, sehingga berlaku hukum kekekalan energi,

$$E + m_e c^2 = E' + E_e \;\Leftrightarrow\; E_e = hf - hf' + m_e c^2. \tag{1.38}$$

dengan E adalah energi foton sebelum tumbukan, $m_e c^2$ energi elektron sebelum tumbukan (berupa energi diam), E' energi foton setelah tumbukan, dan E_e energi elektron setelah tumbukan. Seperti kasus tumbukan pada umumnya, pada peristiwa efek Compton juga berlaku kekekalan momentum.

- Pada arah sumbu x (searah dengan arah datang foton)

$$p = p'\cos\theta + p_e\cos\phi \;\Leftrightarrow\; p^2 + p'^2\cos^2\theta - 2pp'\cos\theta = p_e^2\cos^2\phi \tag{1.39}$$

dengan p momentum foton sebelum tumbukan, p' momentum foton setelah tumbukan, p_e momentum elektron setelah tumbukan, dan ϕ sudut hambur elektron (dihitung terhadap arah foton datang).

- Pada arah sumbu y (tegaklurus arah datang foton)

$$p'\sin\theta = p_e\sin\phi \;\Leftrightarrow\; p'^2\sin^2\theta = p_e^2\sin^2\phi. \tag{1.40}$$

Jumlah dari kedua persamaan terakhir menghasilkan

$$p^2 + p'^2 - 2pp'\cos\theta = p_e^2. \tag{1.41}$$

Dengan mengingat hubungan antara momentum dengan frekuensi, persamaan terakhir dapat ditulis menjadi

$$p_e^2 = \left(\frac{hf'}{c}\right)^2 + \left(\frac{hf}{c}\right)^2 - \frac{2h^2 ff'}{c^2}\cos\theta. \tag{1.42}$$

Di lain pihak, elektron memenuhi persamaan energi relativistik,

$$E_e^2 = (p_e c)^2 + \left(m_e c^2\right)^2. \tag{1.43}$$

Substitusi persamaan (1.38) dan (1.42) ke persamaan terakhir, menghasilkan

$$\left(hf - hf' + m_e c^2\right)^2 = \left[\left(\frac{hf'}{c}\right)^2 + \left(\frac{hf}{c}\right)^2 - \frac{2h^2 ff'}{c^2}\cos\theta.\right]^2 + \left(m_e c^2\right)^2 \tag{1.44}$$

Setelah disederhanakan, persamaan tersebut menghasilkan

$$\begin{aligned} -f'm_e c^2 + fm_e c^2 &= hff' - hff'\cos\theta \\ \Leftrightarrow m_e c^2\left(\frac{c}{\lambda} - \frac{c}{\lambda'}\right) &= \frac{hc^2}{\lambda\lambda'}(1-\cos\theta) \\ \Leftrightarrow \lambda' - \lambda &= \frac{h}{m_e c}(1-\cos\theta)\,, \end{aligned} \tag{1.45}$$

yang menyatakan hubungan antara panjang gelombang foton terhambur (λ') dan sudut hamburannya (θ) dengan panjang gelombang foton datang (λ) dan massa diam elektron (m_e). Persamaan tersebut telah sesuai dengan hasil percobaan.

Notes: Freddy P. Zen lecture notes

Quantum solutions: Wave particle duality

- Light travels as an EM wave
- Light is emitted and absorbed as a stream of particles
- 1924 – Louis de Broglie
  - Particles have wave like properties
  - Confirmed through expt .
    - Electrons shot through crystals form interference pattern
  - 1999 – Anton Zeilenger – Two – slit expt. with C_{60}

Dust particles
$\lambda \sim 6.6 \times 10^{-6}\,\text{Å}$

$$P = \frac{h}{\lambda} = mv\,; \quad k = \frac{2\pi}{\lambda}$$

$$P = \frac{hk}{2\pi} = \hbar k$$

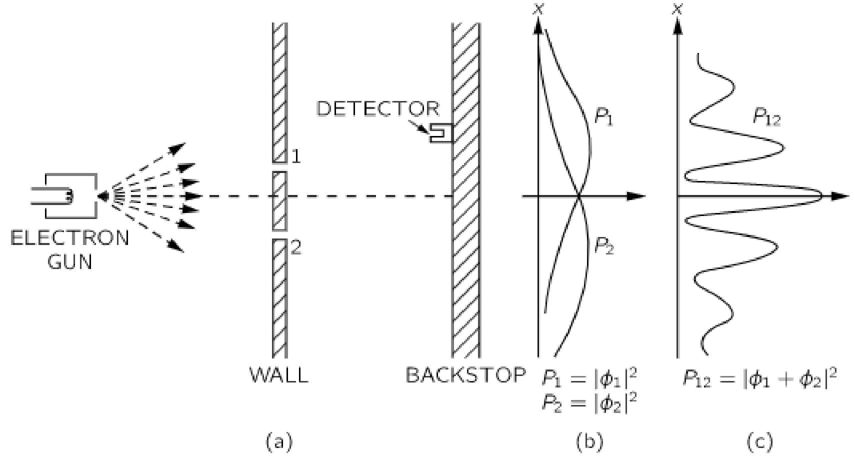
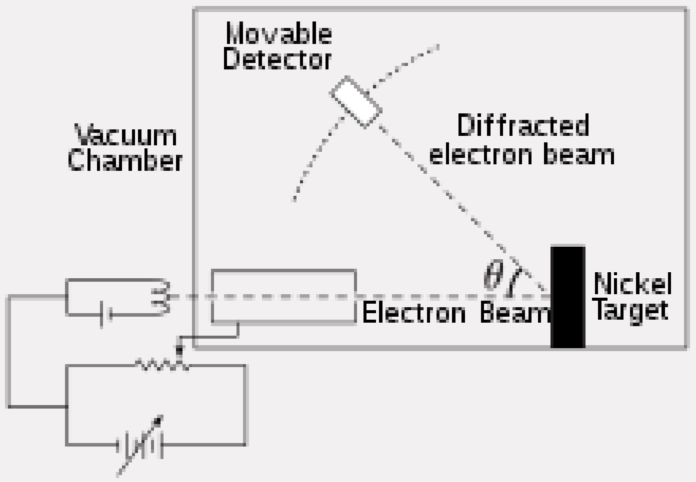


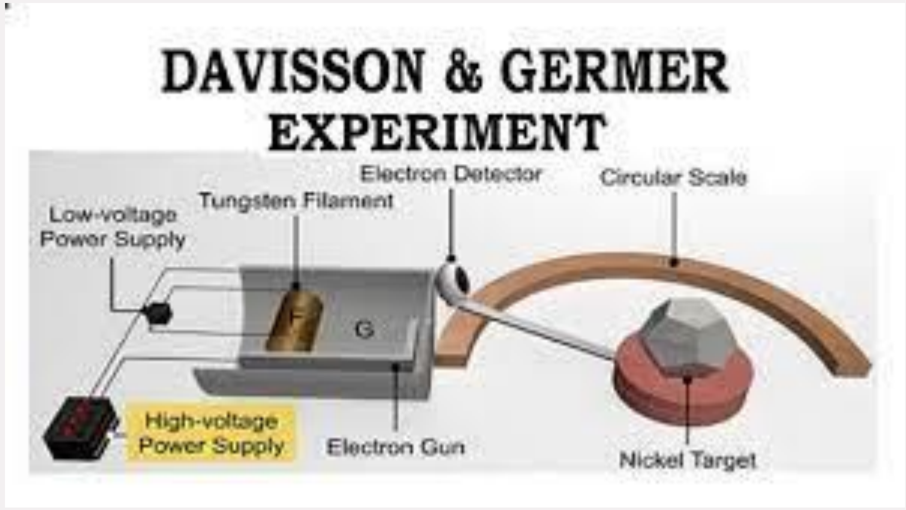
Fig. 1–3. Interference experiment with electrons.

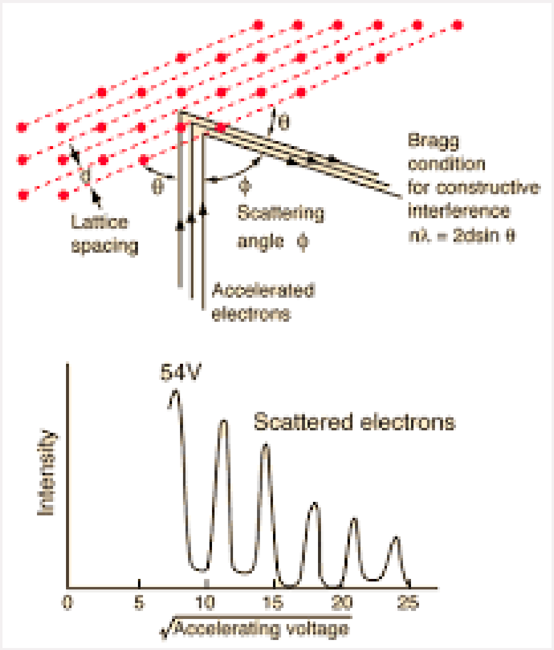
- $hf = mc^2$
- $hf = (mc)c$
  - mc is the momentum of the wave = p
- $hf = pc$
  - $v = f\lambda$
- $hf = p(f\lambda)$
- $h = p\lambda$
- So $p = h / \lambda$

Quantum solutions: Proving wave-particle duality

- Davisson-Germer experiment proved that electron behave like a wave

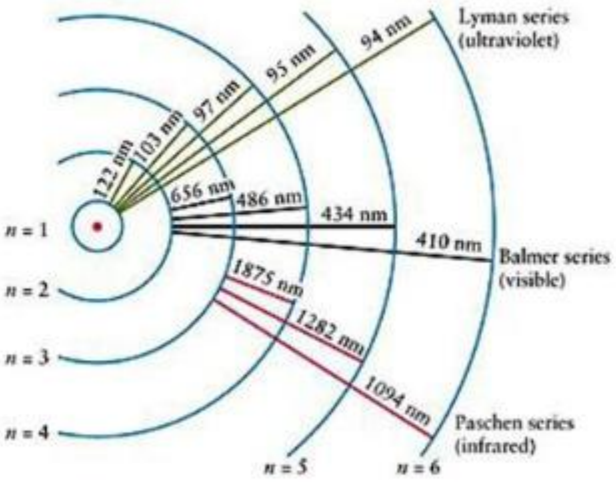


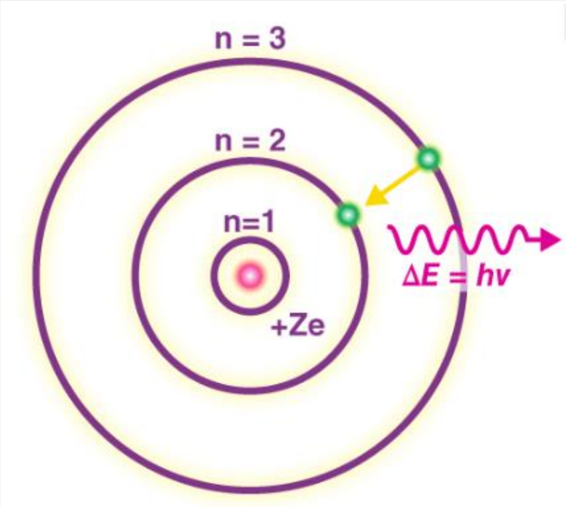




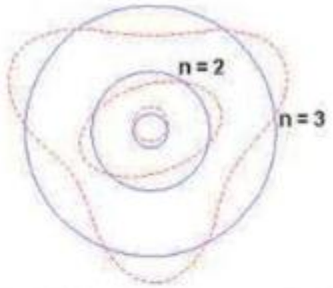
Quantum solutions: Quantum theory of atom

- Bohr's model (1913)
  - Electron's orbits are stationary states
  - If electron jumps from high energy orbit to lower energy orbit it emits photons.





- De Broglie (1924)
  - Bohr orbits explained by standing electron waves
  - Only certain wave patterns allowed
    - Only certain frequencies
    - Only certain energies
  - Standing waves are Bohr's orbits



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

Bohr's condition, that the angular momentum is an integer multiple of $\hbar$
orbit:

$$n\lambda = 2\pi r.$$

According to de Broglie's hypothesis, matter particles such as the electron behave as waves. The de Broglie wavelength of an electron is

$$\lambda = \frac{h}{mv},$$

which implies that

$$\frac{nh}{mv} = 2\pi r,$$

or

$$\frac{nh}{2\pi} = mvr,$$

where mvr is the angular momentum of the orbiting electron. Writing ℓ for this angular momentum, the previous equation becomes

$$\ell = \frac{nh}{2\pi},$$

The electron is held in a circular orbit by electrostatic attraction. The centripetal force is equal to the Coulomb force.

$$\frac{m_e v^2}{r} = \frac{Zk_e e^2}{r^2},$$

where m_e is the electron's mass, e is the elementary charge, k_e is the Coulomb constant and Z is the atom's atomic number

This equation determines the electron's speed at any radius:

$$v = \sqrt{\frac{Zk_e e^2}{m_e r}}.$$

$$m_e \sqrt{\frac{k_e Z e^2}{m_e r}} r = n\hbar,$$

so that the allowed orbit radius at any n is

$$r_n = \frac{n^2 \hbar^2}{Zk_e e^2 m_e}.$$

The smallest possible value of r in the hydrogen atom ($Z = 1$) is called the Bohr radius and is

$$r_1 = \frac{\hbar^2}{k_e e^2 m_e} \approx 5.29 \times 10^{-11} \text{ m}.$$

The energy of the n-th level for any atom is determined by the radius and quantum number:

$$E = -\frac{Zk_e e^2}{2r_n} = -\frac{Z^2 (k_e e^2)^2 m_e}{2\hbar^2 n^2} \approx \frac{-13.6 Z^2}{n^2} \text{ eV}.$$

$$E = E_i - E_f = R_{\mathrm{E}} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right),$$

where n_f is the final energy level, and n_i is the initial energy level.

Since the energy of a photon is

$$E = \frac{hc}{\lambda},$$

the wavelength of the photon given off is given by

$$\frac{1}{\lambda} = R \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right).$$

Quantum Solutions: A Brief Summary

- The blackbody radiation problem solved by stating that the radiation energy is not continuous but consist of chunk or discrete package (quanta)
- The photoelectric effect could be explained by stating that light consist of localized particles called photon which carry discrete energy proportional to the frequency
- Wave-Particle duality: Sometimes light behave as particle, sometimes particle behave as wave (De Broglie wave)
- Bohr model of Atom: Discrete energy level & Discrete angular momentum

OUTLINE

- Classical-Physics Foundations
- Crack in Classical Physics
- Quantum solutions
- Quantum postulates & foundation
- General applications
- Summary & Outlook
- Philosophical discussions

Quantum Postulates & Foundations: Scrodinger equation

- Einstein given the task to apply the Bohr/de Broglie model to atoms other than Hydrogen
  - Was too busy working on GUT so he passed the task on to his friend Erwin Schrodinger
  - Schrodinger was an unpopular choice in that he was considered a failed Physicist!

Perbedaan antara Fisika klasik dan kuantum dapat dipandang dari dua sisi: formulasi dan pengamatan. Pada tingkat perumusan (formulasi), dinamika partikel dalam Fisika klasik digambarkan oleh hukum dinamika Newton,

$$\sum \vec{F} = m\frac{d^2\vec{x}}{dt^2} = \frac{d\vec{p}}{dt}, \tag{2.1}$$

dengan solusi berupa ruang fasa $\{\vec{r}, \vec{p}\}$. Sedangkan pada fisika kuantum, dinamika sistem digambarkan oleh persamaan Schrödinger,

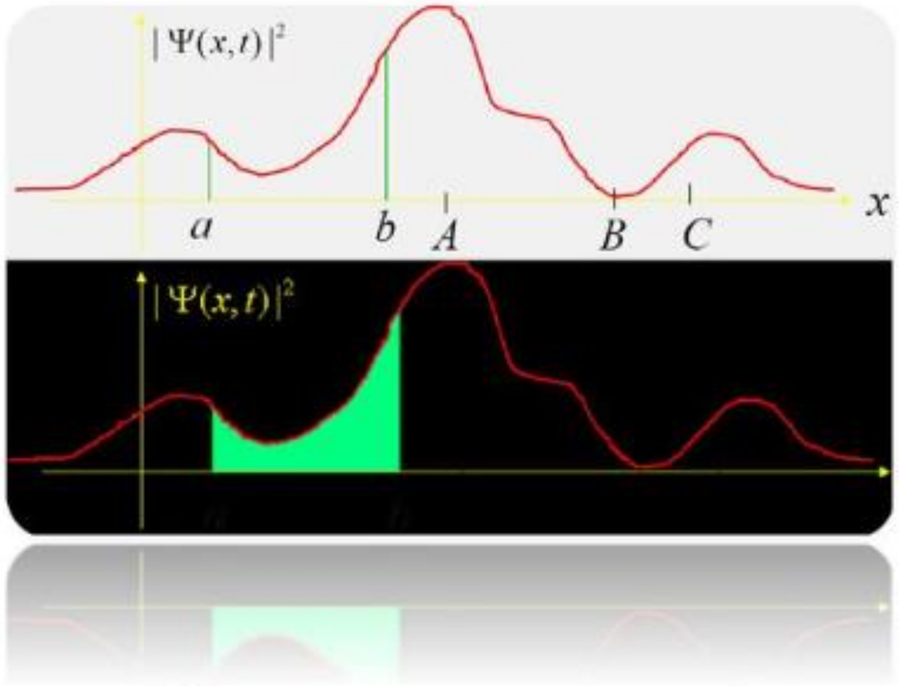
$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r},t)\right)\Psi(\vec{r},t) = E\Psi(\vec{r},t), \tag{2.2}$$

dengan solusi $\Psi(\vec{r},t)$ disebut *fungsi gelombang*, *vektor keadaan*, atau *amplitudo probabilitas*. Fungsi $\Psi(\vec{r},t)$ tidak memiliki makna fisis, namun informasi fisis bisa didapatkan darinya.

Quantum Postulates & Foundations: Interpretation

- Max Born's (1926) statistical interpretation

- $|\Psi(x,t)|^2$
  - gives the probability of finding the particle at point x, at time t



- $\int_a^b |\Psi(x,t)|^2\, dx$
  - Probability of finding the particle between a and b, at time t.

- $\int_{-\infty}^{\infty} |\Psi(x,t)|^2\, dx = 1$
  - Probability of finding particle in the universe should be 1.

Quantum Postulates & Foundations: Postulates

1. The state of QM system is completely specified by $\Psi(x,t)$.

   – $|\Psi(x,t)|^2\,dx$ is the probability of finding the particle between x and $x + dx$

$$\int_{-\infty}^{\infty} |\Psi(x,t)|^2\,dx = \int_{-\infty}^{\infty} \Psi^*(x,t)\Psi(x,t)dx = 1$$

   – $\Psi(x,t)$ and $\frac{\partial\Psi(x,t)}{\partial x}$ are continuous. $\Psi(x,t)$ is finite and single valued.

Quantum Postulates & Foundations: Postulates

2. For every observable (dynamic variable) in classical mechanics – Position, momentum, energy etc. there exists a linear operator in QM.
   - For position X, momentum $\frac{\hbar}{i}\frac{\partial}{\partial x}$
   - Ensemble average (Expectation value) of $\hat{A}$ are real
     - $\langle \hat{A} \rangle = \langle \hat{A} \rangle^*$
     - $\langle \hat{A} \rangle = \int_{-\infty}^{\infty} \Psi^*(x,t)\hat{A}\Psi(x,t)dx$
     - All QM operators are “Hermitian”

Quantum Postulates & Foundations: Postulates

3. 1. Measurement of $\hat{A}$ will only yield the values *a* which satisfy the equation.

$$\hat{A}\Psi = a\Psi$$

- Eigen value equation
- Eigen values a are real numbers
- Central point of QM – dynamic variables are quantized
- Only hermitian operators will yield real eigen values.

Quantum Postulates & Foundations: Postulates

3. 2. Each eigen value has an “eigen state” associated with it
   - Initial state of system can be arbitrary.
   - Can be expanded in the complete set of eigen states.

$$\hat{A}\psi_i = a_i\psi_i \qquad \Psi = \sum_i^n c_i\psi_i$$

   - $\hat{A}$ will yield one of the eigen values a_i
   - Probability that a_i will occur is $|c_i|^2$

Quantum Postulates & Foundations: Postulates

4. State of system (wave function) evolves according to *Time dependent Schrödinger equation* (TDSE).

$$\boxed{\hat{\mathrm{H}}\Psi(x,t) = i\hbar\frac{\partial\Psi}{\partial t}}$$

– Where $\hat{\mathrm{H}} = \frac{\hbar^2}{2m}\frac{\partial^2}{\partial^2 x} + V$

Quantum Postulates & Foundations: Postulates

Uncertainty

- Expectation value of $\hat{A}$

$$\langle\hat{A}\rangle = \int_{-\infty}^{\infty} \Psi^*(x,t)\hat{A}\Psi(x,t)dx$$

$$\langle\hat{A}\rangle = \langle\Psi|\hat{A}|\Psi\rangle$$

- Uncertainity in $\Delta\hat{A}$

$$\Delta\hat{A} = \langle\Psi|(\hat{A} - \langle\hat{A}\rangle)^2|\Psi\rangle$$

- Expectation value and uncertainty provides a good description of the system
  - E.g. If for a particle $\langle X\rangle = a$ and $\Delta X = \Delta$ then we know it can be spotted at $x = a$ with deviation of order Δ

Quantum Postulates & Foundations: Back to electron diffraction (electron as a wave)

- Normal electron interference experiment:

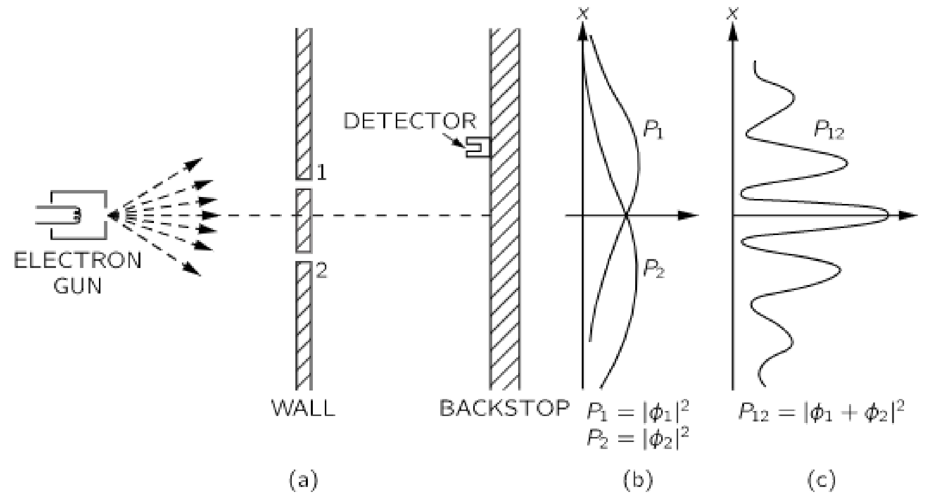


Fig. 1–3. Interference experiment with electrons.

- What happen if we look into the slit to see which slit is passed by each electron?

Quantum Postulates & Foundations: Back to electron diffraction (electron as a wave)

- The interference term disappear

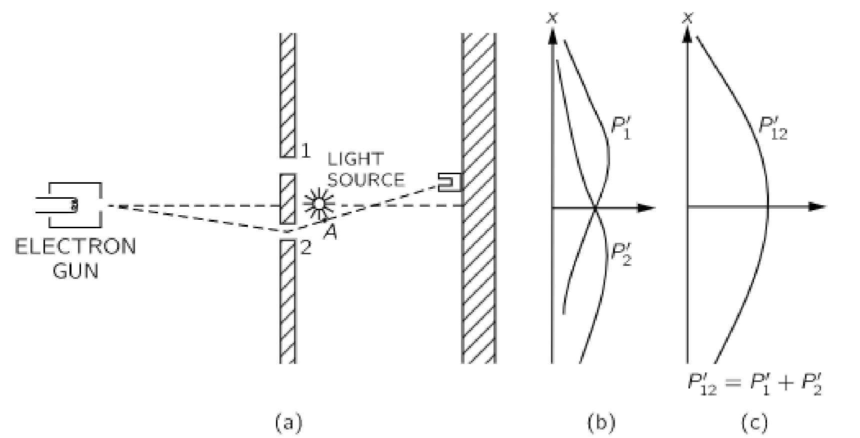


Fig. 1–4. A different electron experiment.

- But Why?

Quantum Postulates & Foundations: Back to electron diffraction (electron as a wave)

QM – Interpretation of Motion

- Quantum mechanics does not predict precise trajectories
- Quantum mechanics does not predict the exact position of a particle.
  - Instead it predicts the probability of finding a particle in different locations.
- The electron exists in an undetermined state until measurement.
  - This interaction causes the electron to materialize at some position in space, determined randomly but weighted by the probability distribution of the wave function.
- The predictions of quantum mechanics coincide with those of classical mechanics for heavy Particles

Subjectivism

Quantum Postulates & Foundations: Heisenberg Uncertainty

Heisenberg’s Uncertainty Principle

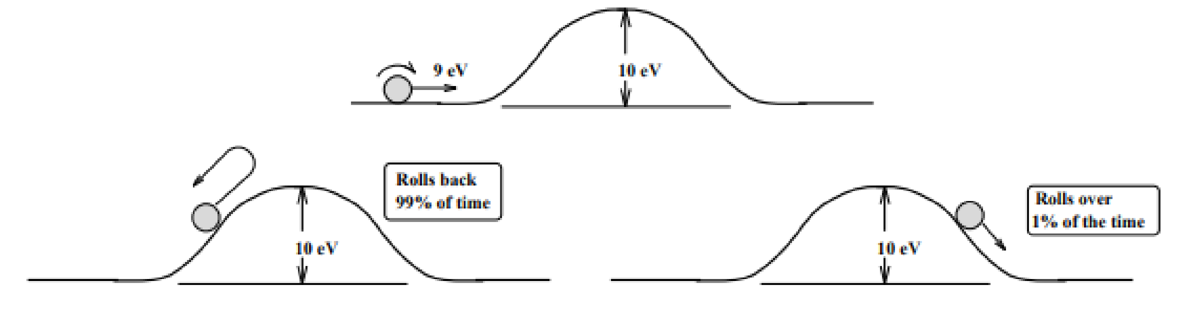
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

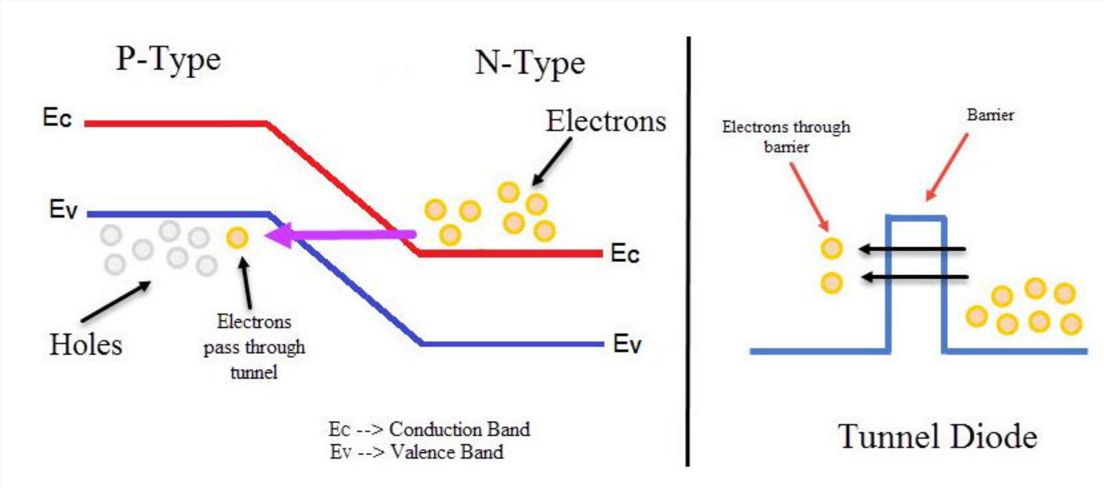
- Position and momentum of a particle cannot be known with infinite precision at the same time.
- Also same for energy and time

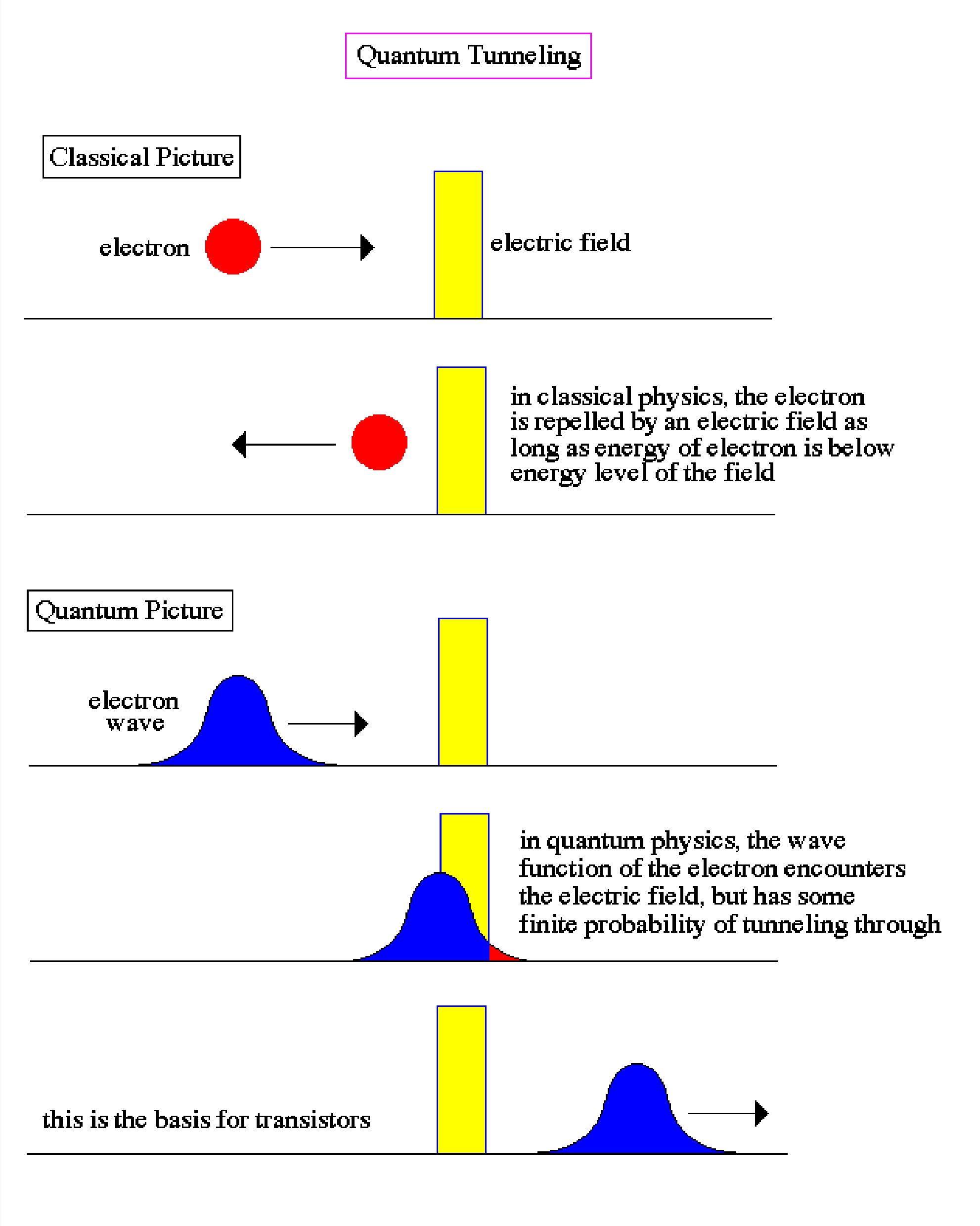
$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

OUTLINE

General Application: Tunneling effect







Other application: Computer, mobile phone, laser, MRI, solar cell, GPS, electron microscope, and many more…. Quantum exist in our daily life

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Summary & Outlook

Classical Physics	Quantum Physics
Work for Macroscopic object	Work for Microscopic object
Deterministic	Probabilistic
In principle we could measure any observables with unlimited precision	Heisenberg principle prevent from unlimited precision for some measurements
Continuous energy	Discrete energy
Distinct feature of particle and wave	Wave-particle dualism
Objectivism	Subjectivism
Find observable (trajectory) by solving newton equation or Maxwell equation. For example, $v(t)$, $x(t)$	Find ψ by solving Scrodinger equation. Ψ itself does not have physical meaning. But from ψ we could calculate probability of certain particle at some position, calculate the expectation value for some observables via operator, etc

Outlook: You will learn to find ψ from various potential setting (Infinite well, oscillator harmonic, Hydrogen atom, etc) and get various physical observables from ψ

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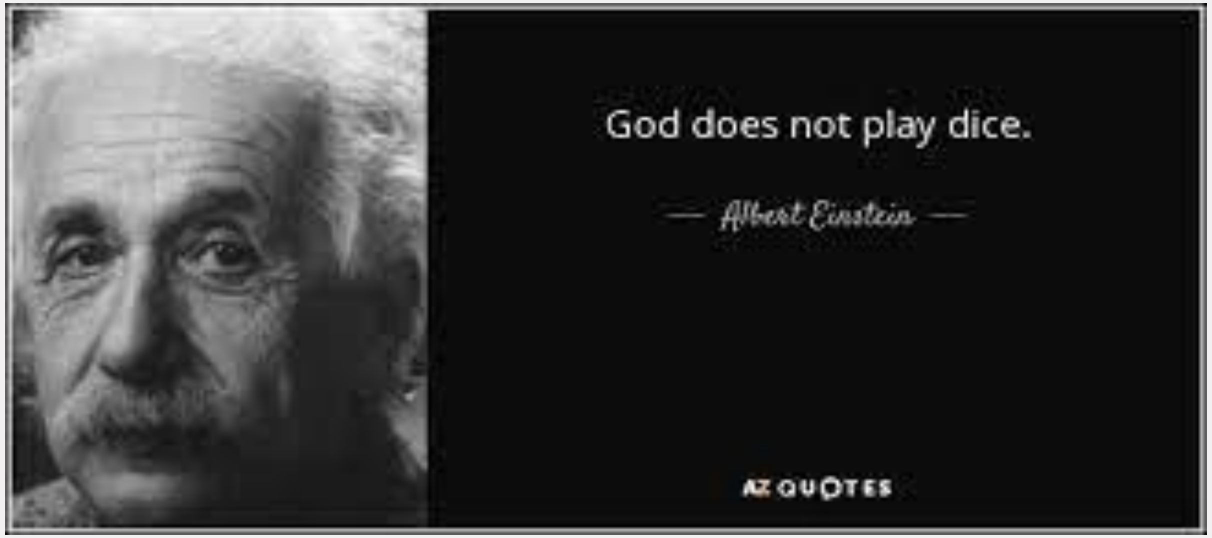
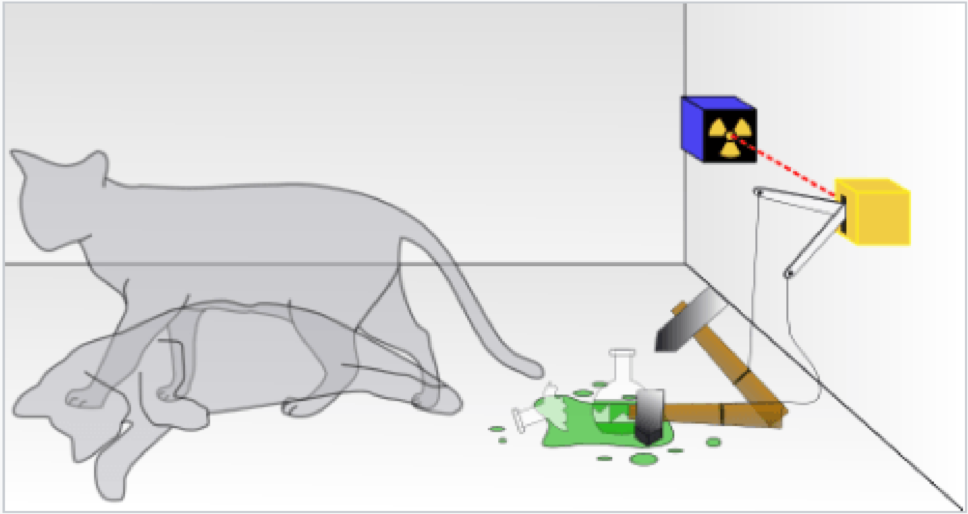
Philosophical discussions



Wave-Particle duality: light behave as wave in the double-slit experiment and behave as particle (photon) in photoelectric effect. How do they know what equipment in front of them and when do they decide to behave as wave or particle?



Schrödinger's cat: a cat, a flask of poison, and a radioactive source are placed in a sealed box. If an internal monitor (e.g. Geiger counter) detects radioactivity (i.e. a single atom decaying), the flask is shattered, releasing the poison, which kills the cat. The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is *simultaneously* alive *and* dead. Yet, when one looks in the box, one sees the cat *either* alive *or* dead, not both alive *and* dead. This poses the question of when exactly quantum superposition ends and reality collapses into one possibility or the other.

Thank You

Any Questions?