Chapter 1

Experimental Foundations

Lecture 2: Experiments beyond classical physics

2026.09.07

> **Questions.**
> What experimental facts must our models of matter and radiation explain?

1.5 Experiments beyond classical physics

The purpose of this lecture is to identify the experimental facts that any successful theory of microscopic systems must explain. We will focus on six:

- Atoms exist and contain electrons and nuclei.
- Randomness is present in individual physical events, although repeated experiments have reproducible probabilities.
- Atomic spectra are discrete and structured.
- The photoelectric effect shows that light exchanges energy in packets.
- Electrons diffract and interfere in ways that are not described by classical particles.
- Bell's inequality provides a final test that rules out a broad class of classical descriptions.

These observations will guide the construction of quantum mechanics.

1.5.1 Atoms and nuclei exist

Experimental evidence for electrons

Cathode-ray tubes A cathode-ray tube (CRT) uses an electron gun to direct a beam onto a phosphorescent screen. Electrons striking the screen produce light, and electric or magnetic fields can steer and focus the beam. A CRT therefore demonstrates that electrons can be produced, controlled, and detected.

Bubble-chamber tracks The Gargamelle bubble chamber at CERN contained roughly $30\,\mathrm{m}^3$ of liquid freon close to its vapor pressure. A charged particle passing through the liquid ionizes atoms and molecules along its path.

When the liquid is rapidly expanded, bubbles form at these ionization sites and record the particle's trajectory.

Figure 1.1 records a neutrino scattering from an atomic electron. The incoming neutrino is electrically neutral and leaves no visible track; the recoiling electron is charged and produces the thin white bubble trail. The photograph is therefore direct evidence that the trajectory of an individual electron can be detected.

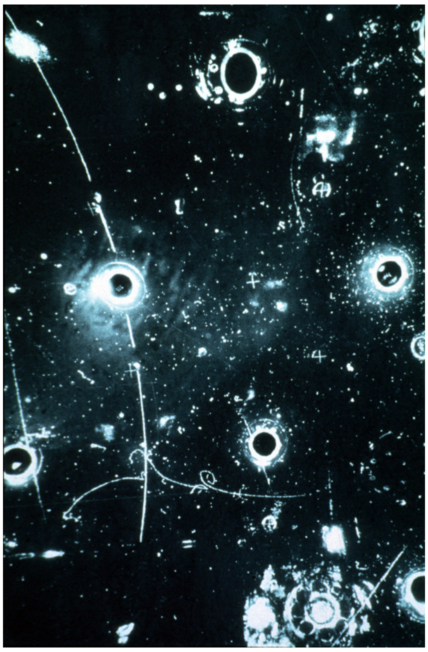


Figure 1.1: A Gargamelle bubble-chamber event. The thin white trail records the recoiling electron after a neutrino–electron scattering event; the incoming neutrino leaves no visible track.

Together, cathode-ray tubes and bubble chambers provide experimental evidence for electron beams and individual electrons.

Experimental evidence for nuclei

Setup and expectation Rutherford, Geiger, and Marsden directed positively charged α particles at a thin gold foil and recorded the particles on a surrounding screen. If the atom were a diffuse distribution of charge and mass, the α particles should be deflected only slightly.

Observation Most particles passed through with small deflections, but a small fraction scattered through very large angles, sometimes $160°$–$180°$.

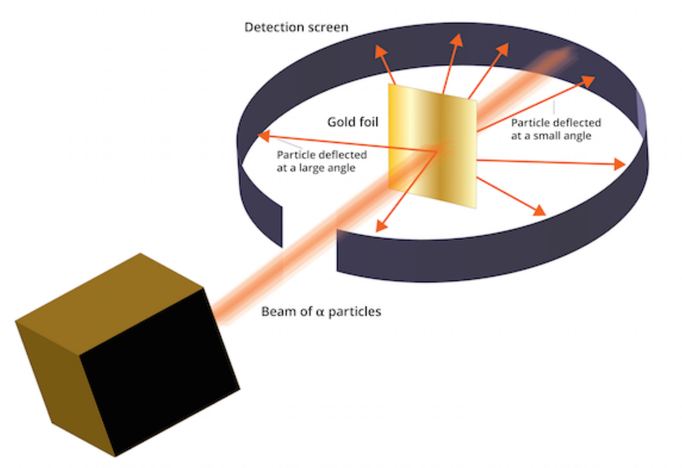


Figure 1.2: Schematic of the Rutherford–Geiger–Marsden scattering experiment. A beam of positively charged α particles is directed at a thin gold foil, and a surrounding screen records where the particles arrive. The red lines represent different possible particle trajectories: most particles pass through with only a small deflection, while a small fraction scatter through large angles.

Inference The large-angle events show that an atom is mostly empty space with a very small, dense, positively charged core containing most of its mass. This core is the atomic nucleus. Together with the electron evidence above, the experiment establishes the basic substructure of atoms: electrons surround compact nuclei.

> **Proposition 1** (Experimental result 1). Atoms contain electrons and compact, positively charged nuclei. Cathode-ray tubes and bubble chambers provide evidence for electrons, while large-angle α-particle scattering provides evidence for nuclei.

The classical stability problem

The nuclear model immediately exposes a problem for classical physics. A classical electron orbiting a positive nucleus is accelerating, so it should radiate energy. It would lose energy and angular momentum, spiral inward, and rapidly collide with the nucleus. Classical electrodynamics therefore cannot explain the observed stability of atoms. Explaining stable matter is one of the first challenges for quantum mechanics.

Further applications of scattering

SLAC In deep-inelastic experiments at SLAC, high-energy electrons were scattered from protons. The results showed that protons contain point-like constituents, described in the simplified quark model.

RHIC Collisions of relativistic heavy nuclei at Brookhaven's RHIC produce a short-lived, extremely hot and dense state of quark and gluon matter called the quark–gluon plasma. Unlike the SLAC experiments, the primary purpose is to create and study this collective state of matter rather than to determine whether a single proton has internal structure.

1.5.2 Randomness is reproducible

Reproducible randomness means that repeated experiments need not give the same individual outcome, even when the preparation and apparatus are fixed, but they do reproduce the same probability distribution.

Measurement boxes Electrons selected from the Hard output of a hardness box split approximately 50–50 between Black and White when color is measured. Each electron produces one definite result, but the experiment does not predict which result a particular electron will produce. Repeating the same preparation many times reproduces the 50–50 distribution.

Radioactive decay An unstable nucleus emits radiation at an unpredictable time. A Geiger–Müller counter converts each detected radiation event into an electrical pulse. The counter contains a gas between electrodes held at a high voltage, below the voltage for spontaneous discharge. A charged particle passing through the gas ionizes its atoms,

$$\mathrm{A} \longrightarrow \mathrm{A}^{+} + e^{-}. \tag{1.1}$$

The electric field accelerates the liberated electrons, which ionize additional atoms and produce an avalanche of charge. The resulting current pulse is recorded as one count or click.

Statistical regularity The time of the next click cannot be predicted, because the decay time of an individual nucleus is random. Nevertheless, repeated measurements of the same radioactive sample give a reproducible average count rate and decay law. The Geiger counter therefore illustrates the same distinction as the measurement boxes: individual events are unpredictable, while their statistical distribution is stable.

Proposition 2 (Experimental result 2)**.** For a fixed preparation, quantum mechanics predicts reproducible probabilities for possible outcomes even when it does not predict the outcome of an individual trial.

1.5.3 Discrete atomic spectra

Experiment Put a gas such as hydrogen or neon in a discharge tube and excite it electrically. The gas emits light. Send this light through a prism or diffraction grating and measure the intensity as a function of wavelength.

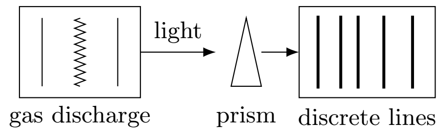


Figure 1.3: A gas discharge produces discrete atomic emission lines.

Observation Instead of a continuous rainbow, an excited atom emits light only at certain sharp wavelengths. Changing the power source or the prism can change the brightness of the lines, but not their positions. Changing the gas changes the set of wavelengths. Each atomic species therefore has a characteristic spectrum.

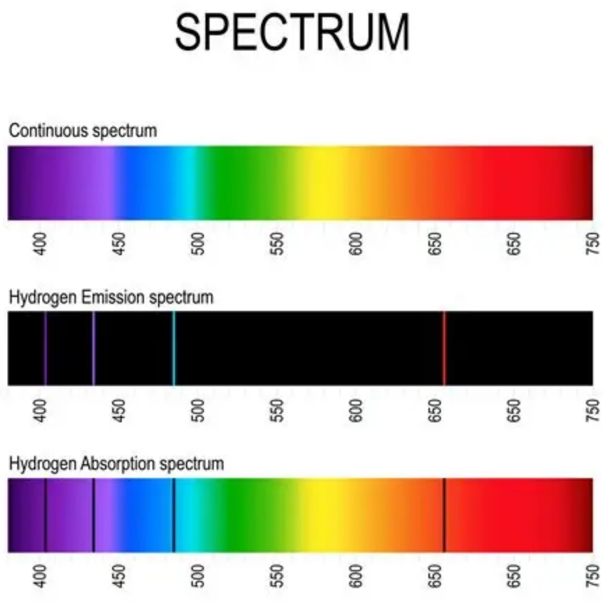


Figure 1.4: Comparison of a continuous spectrum with the visible emission and absorption spectra of hydrogen. The four prominent hydrogen emission lines shown are the visible Balmer lines near 410.2, 434.0, 486.1, and 656.3 nm.

Emission and absorption Figure 1.4 compares three spectra. A continuous spectrum contains light throughout the visible range. Excited hydrogen gives an emission spectrum with bright lines at selected wavelengths. Hydrogen gas can also absorb those same wavelengths from continuous light, producing dark absorption lines at corresponding positions.

The four hydrogen emission lines shown in Figure 1.4 are the visible Balmer lines near 410.2, 434.0, 486.1, and 656.3 nm. They are not the complete hydrogen spectrum. The Lyman series lies in the ultraviolet, the Balmer series contains the visible lines, and the Paschen series lies in the infrared. So these three series correspond, respectively, to ultraviolet, visible, and infrared light.

Empirical structure The visible Balmer wavelengths are well described by

$$\lambda_n \simeq (364.6\,\text{nm})\frac{n^2}{n^2-4} = (364.6\,\text{nm})\left(1-\frac{4}{n^2}\right)^{-1}, \qquad n = 3,4,5,\ldots. \tag{1.2}$$

This formula was first an empirical fit: it reproduced the observed lines before there was a physical explanation. Rydberg and Ritz then found that all hydrogen lines can be organized by

$$\frac{1}{\lambda} = R_{\text{H}}\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right), \qquad n_1, n_2 \in \mathbb{Z}, \quad n_2 > n_1, \tag{1.3}$$

where $R_{\text{H}} \simeq 1.097 \times 10^7\,\text{m}^{-1}$. The integer $n_1 = 1$ gives the Lyman series, $n_1 = 2$ gives the Balmer series, and $n_1 = 3$ gives the Paschen series. The appearance of integers is the important clue: atomic radiation is discrete and highly structured, not a continuous spread of possible frequencies.

Classical problem A classical model with electrons moving in arbitrary orbits gives no natural reason for only these wavelengths to appear. Quantum mechanics must explain why atoms emit and absorb only certain frequencies.

> **Proposition 3** (Experimental result 3)**.** Atomic spectra are discrete and structured. Each atomic species emits a characteristic set of frequencies rather than an arbitrary continuous range.

1.5.4 The photoelectric effect

Setup Shine light of frequency ν on a metal surface. Electrons may be ejected from the metal and collected by a second plate, producing a current I. To measure the maximum kinetic energy of the emitted electrons, apply a reverse voltage that opposes their motion. The stopping voltage V_0 is the magnitude of the reverse voltage at which the photocurrent falls to zero. If q_e denotes the magnitude of the electron charge, then $K_{\max} = q_e|V_0|$.

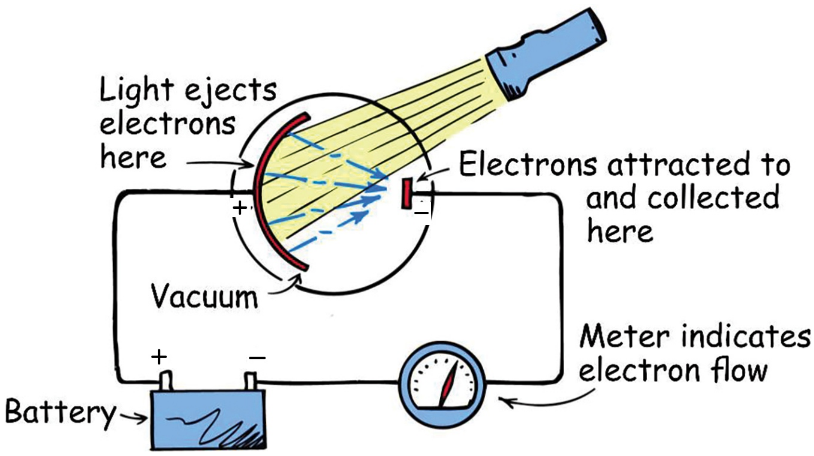


Figure 1.5: A photoelectric-effect apparatus with a reverse bias. The illuminated source plate is positive and the collector is negative, so the electric field opposes the motion of the emitted electrons. Increasing this opposing voltage until the photocurrent vanishes determines the stopping voltage.

Classical expectation In classical electromagnetic theory, the energy carried by a light wave is controlled by the field amplitude, so the intensity is proportional to A^2. The natural expectation is that increasing the intensity should eject more energetic electrons and therefore increase $|V_0|$. Frequency should not be the quantity that controls the maximum electron energy.

Observation The experiment gives a different result:

(i) for fixed ν, increasing the intensity increases the photocurrent;

(ii) for fixed ν, the stopping voltage is independent of intensity;

(iii) $|V_0|$ varies linearly with ν;

(iv) below a threshold frequency no electrons are emitted, regardless of how intense the beam is;

Figure 1.7 shows the key comparison. The high-intensity beam gives a larger current, so it ejects more electrons per unit time. However, both curves reach zero current at the same stopping voltage. Thus intensity controls the number of emitted electrons, while frequency controls the maximum kinetic energy of each emitted electron.

Frequency dependence The real surprise is that the stopping voltage does not depend on intensity. Instead, the magnitude of the stopping voltage increases linearly with the frequency and vanishes at a threshold frequency ν_0. Very low-frequency light can be intense and still fail to eject electrons, while weak high-frequency light can eject electrons that are hard to stop.

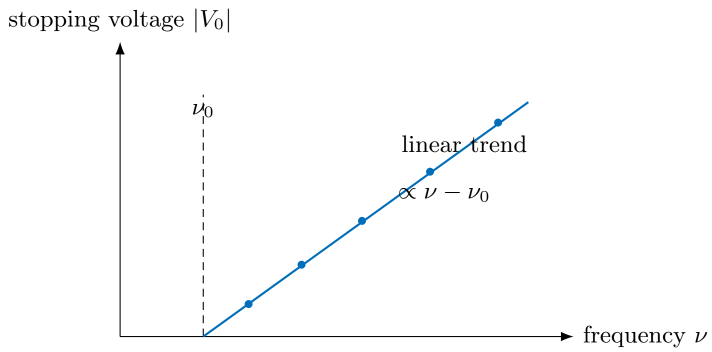


Figure 1.6: The stopping voltage magnitude varies linearly with frequency and vanishes at the threshold frequency ν_0.

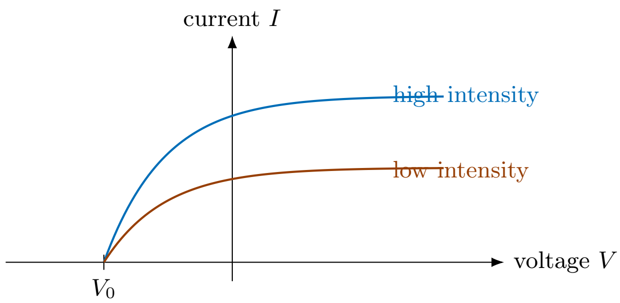


Figure 1.7: Changing the intensity changes the photocurrent but not the stopping voltage V_0.

Einstein's explanation Einstein proposed that light exchanges energy in packets, now called photons. Each photon has energy proportional to its frequency, while intensity measures how many photons arrive per unit time. If W is the work required to extract an electron from the metal, then

$$E_{\text{photon}} = h\nu, \qquad K_{\max} = h\nu - W, \qquad q_e|V_0| = K_{\max} \tag{1.4}$$

The threshold frequency is $\nu_0 = W/h$. Below this frequency one photon does not supply enough energy to release an electron. Above threshold, $K_{\max}$ and $|V_0|$ increase linearly with frequency. Increasing the intensity supplies more photons, so it increases the current but not the maximum energy of each emitted electron.

Photon momentum The constant h is Planck's constant, and $\hbar = h/(2\pi)$. For light, $E = cp$ and $c = \lambda\nu$. Combining these relations with $E = h\nu$ gives

$$p = \frac{h}{\lambda} = \hbar k, \qquad k = \frac{2\pi}{\lambda}. \tag{1.5}$$

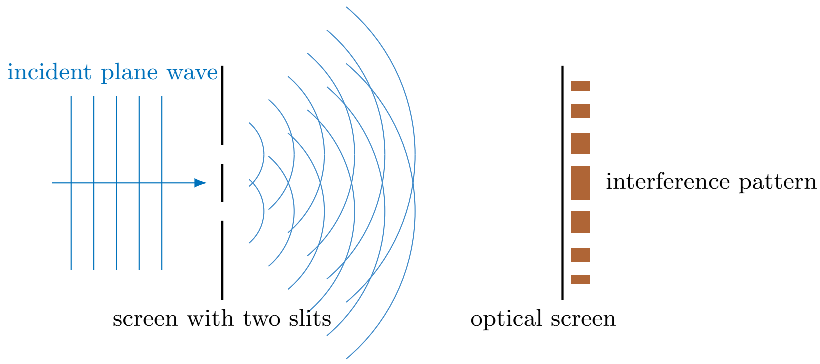
Planck had introduced the same relation $E = h\nu$ in blackbody radiation as a rule for quantized energy exchange. Einstein took it seriously as a statement about light itself. The photoelectric effect therefore gives direct evidence that light exchanges energy and momentum in discrete packets.

Proposition 4 (Experimental result 4). The photoelectric effect shows that light exchanges energy and momentum in discrete packets. The photon relations are $E = h\nu$ and $p = h/\lambda$.

1.5.5 Interference and the double slit

Why light is also a wave

Experiment The photoelectric effect shows that light exchanges energy in packets. Young's double-slit experiment shows that light also propagates as a wave. In the experiment, an incident wave reaches a barrier with two narrow slits. The two slits act as coherent sources, and the waves arriving at a distant screen add. Some points receive waves in phase and become bright; other points receive waves out of phase and become dark.



Schematic double-slit experiment: the two slits act as coherent sources, and the screen records an interference pattern.

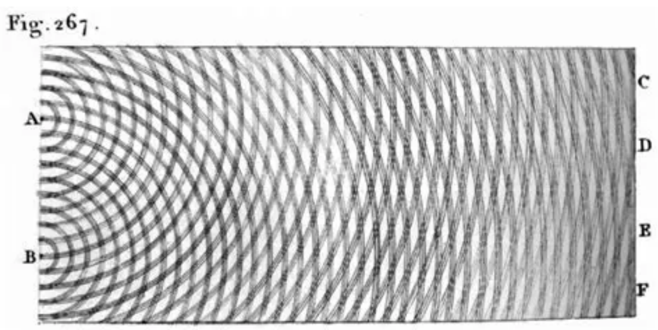


Figure 1.8: Young's original hand-drawn diagram of two-slit interference.

Interference condition Two identical narrow slits are separated by ℓ, and the screen is a distance D away. At a point P on the screen, the two waves travel slightly different distances. The path difference is approximately $\ell \sin\theta$. Constructive interference occurs when this path difference is an integer number of wavelengths:

$$\ell \sin\theta = \lambda n, \qquad n \in \mathbb{Z}. \tag{1.6}$$

For $D \gg \ell$ and small θ, $\sin\theta \simeq y/D$, so the bright fringes satisfy

$$\ell y \simeq D\lambda n, \qquad n \in \mathbb{Z} \tag{1.7}$$

where y is the vertical displacement from the central maximum.

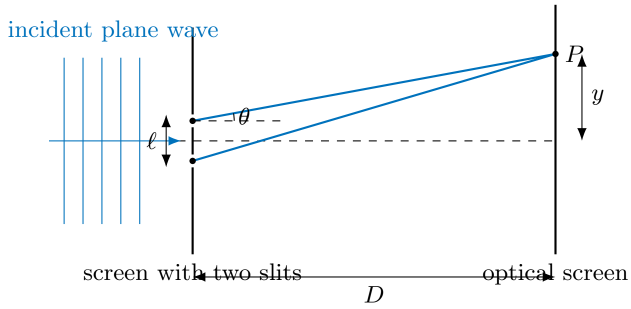


Figure 1.9: Geometry for two-slit interference. The path difference between the two waves is controlled by the slit separation and the angle to the observation point on the screen.

Amplitude and intensity A wave has an amplitude, while the screen records intensity. Let the two possible paths contribute amplitudes $A_1(y)$ and $A_2(y)$. For equal magnitudes, the total amplitude is

$$A(y) = A_0 \left(\exp(i\theta_1(y)) + \exp(i\theta_2(y))\right). \tag{1.8}$$

The measured intensity is proportional to the squared magnitude of the total amplitude:

$$|A(y)|^2 = 2A_0^2 \left[1 + \cos\bigl(\theta_1(y) - \theta_2(y)\bigr)\right] \simeq 2A_0^2 \left[1 + \cos\left(\frac{2\pi\ell y}{\lambda D}\right)\right]. \tag{1.9}$$

The interference fringes come from the cross term in $|A_1 + A_2|^2$. Classical probabilities would add as $P_1 + P_2$; waves add amplitudes first and only then square the result.

Conclusion Light has both experimentally established features. In the photoelectric effect, energy is exchanged in localized packets. In the double-slit experiment, propagation is described by interfering wave amplitudes.

Suggested reading.

- Feynman, Leighton, and Sands, *The Feynman Lectures on Physics*, Vol. III, Ch. 1, *Quantum Behavior*, Secs. 1–4 through 1–7. Optional background: Secs. 1–2 and 1–3.
- Susskind and Friedman, *Quantum Mechanics: The Theoretical Minimum*, Ch. 1, *Systems and Experiments*, Secs. 1.1–1.4, especially Sec. 1.3, *An Experiment*, and Sec. 1.4, *Experiments Are Never Gentle.*