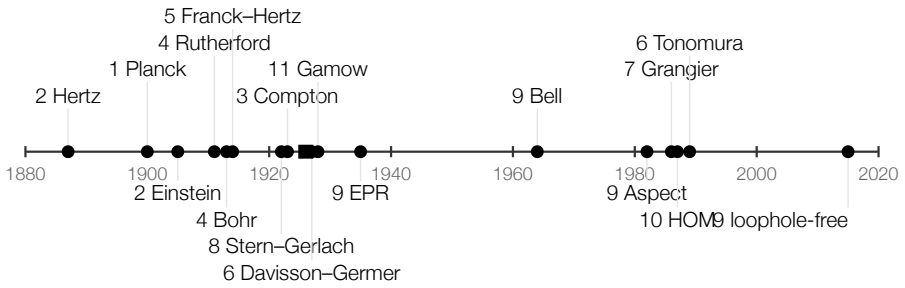
0 · The Experiments Behind Quantum Mechanics

Companion to the 8.04 / 8.05 / 8.06 course summaries · apparatus schematics and measured results

Where classical physics broke

1. **Hot objects:** classical theory predicts infinite radiated energy (ultraviolet catastrophe).
2. **Light on metals:** electron energy depends on colour, not brightness; sharp threshold.
3. **Atoms:** an orbiting electron should radiate and collapse in ~10^{-11} s and give a continuous spectrum. Atoms are stable, with sharp lines.
4. **Cold solids:** heat capacities fall to zero as $T \to 0$ instead of staying at $3k_B$ per atom.
5. **Particles vs waves:** light arrives in lumps; electrons interfere.
6. **Magnetic atoms:** angular momentum along any axis takes only discrete values.
7. **Correlations:** entangled pairs beat every local classical model.
8. **Identical particles:** photons and electrons have no individual identity.

Timeline

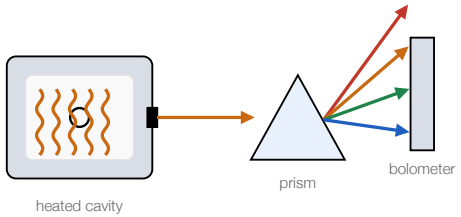


quantum mechanics formulated 1925–27

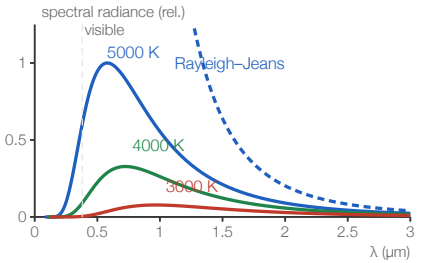
1 Blackbody radiation

Lummer–Pringsheim, Rubens–Kurlbaum 1899–1900 · Planck 1900

energy quanta



A heated cavity with a small hole is a near-perfect blackbody. A prism or grating spreads its light; a bolometer measures power at each wavelength.



Planck's law at three temperatures; Rayleigh–Jeans (dashed) for 5000 K diverges at short λ. Peaks follow Wien's law, $\lambda_{max} T = 2898\ \mu$m·K.

Classical Every cavity mode gets $k_B T$, and there are $\propto \nu^2$ modes, so the energy density grows without bound at high frequency.

Observed The spectrum peaks and falls off; the peak moves to shorter λ as T rises. Today's best blackbody: the cosmic microwave background (COBE 1990, $T = 2.725$ K).

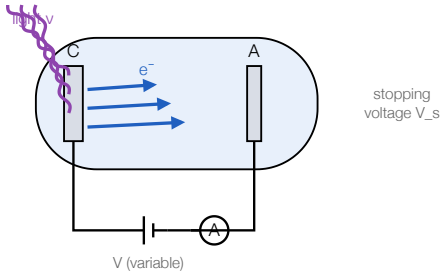
Lesson Oscillators exchange energy only in steps $h\nu$, so high-frequency modes are frozen out. The same idea explains heat capacities vanishing as $T \to 0$ (Einstein 1907).

$$u(\nu, T) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/k_B T} - 1} \xrightarrow{h\nu \ll k_B T} \frac{8\pi\nu^2}{c^3} k_B T$$

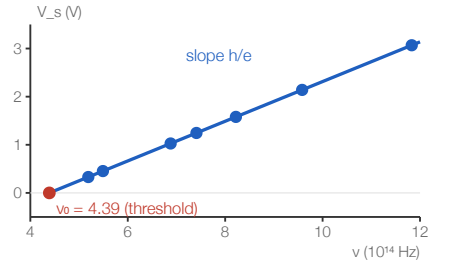
2 Photoelectric effect

Hertz 1887 · Lenard 1902 · Einstein 1905 · Millikan 1916

photons



Light frees electrons from a metal cathode. A reverse voltage is raised until the current stops: the stopping voltage V_s measures the fastest electrons' energy.



Millikan's sodium result: V_s is linear in ν with slope $h/e = 4.12 \times 10^{-15}$ V·s, giving $h = 6.57 \times 10^{-34}$ J·s. Dots: the mercury lines he used.

Classical Brighter light carries more energy, so it should eject faster electrons; any colour should work after a delay.

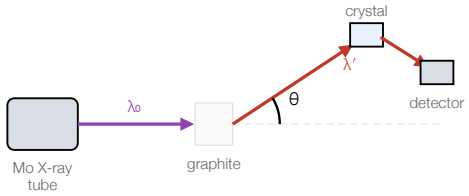
Observed Electron energy depends only on frequency; below a threshold ν_0 nothing comes out however bright; no delay. Intensity changes only the *number* of electrons.

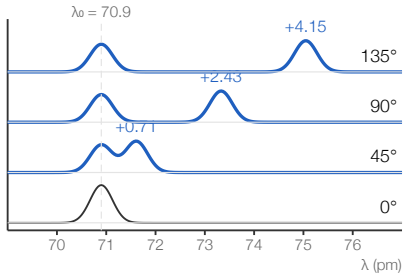
Lesson Light itself comes in quanta (photons), each giving its whole energy $h\nu$ to one electron.

$$eV_s = K_{max} = h\nu - W, \qquad \nu_0 = W/h$$

3 Compton scattering — A. H. Compton 1923

photon momentum





Molybdenum Kα X-rays (λ = 70.9 pm) hit a graphite block. A rotating crystal spectrometer measures the wavelength scattered at angle θ.

Spectra at four angles (redrawn from Compton's values): an unshifted peak from tightly bound electrons and a shifted peak at $\lambda_0 + \lambda_C(1-\cos\theta)$.

Classical An EM wave shakes the electron at its own frequency, so scattered light keeps the same wavelength.

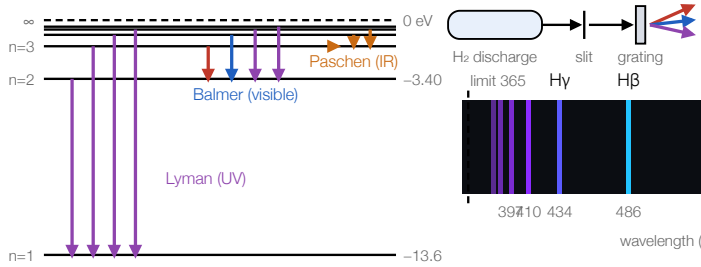
Observed A second, longer-wavelength peak whose shift depends only on angle, not on the target material.

Lesson Photons carry momentum $p = h/\lambda$; the shift is exactly a relativistic billiard-ball collision.

$$\lambda' - \lambda = \frac{h}{m_e c}(1-\cos\theta), \qquad \lambda_C = \frac{h}{m_e c} = 2.43\ \text{pm}$$

4 Atomic spectra & stable atoms — Balmer 1885 · Rutherford 1911 · Bohr 1913

discrete levels



Hydrogen levels $E_n = -13.6/n^2$ eV. Lyman lines end on $n = 1$ (UV), Balmer lines on $n = 2$ (visible).

Hydrogen discharge tube → slit → grating: the visible Balmer lines at 656, 486, 434, 410, 397 nm, crowding toward the 365 nm series limit.

Classical Rutherford's atom (electron orbiting a tiny nucleus) radiates continuously and spirals in within ~10^{-11} s.

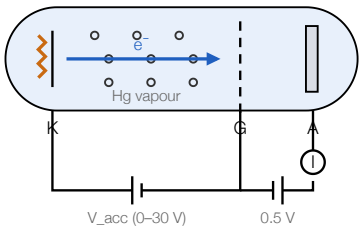
Observed Atoms are stable and emit only sharp, element-specific lines that fit simple integer formulas.

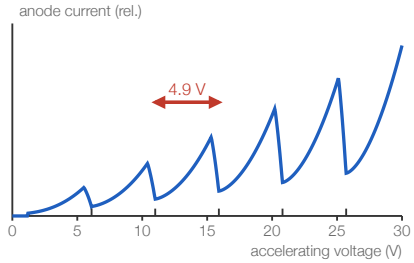
Lesson Bound systems have discrete energies; a photon carries the difference. Stability comes from the uncertainty principle: confining the electron costs kinetic energy.

$$\frac{1}{\lambda} = R_\infty\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right), \quad R_\infty = 1.097\times10^7\ \text{m}^{-1}, \quad h\nu = E_i - E_f$$

5 Franck–Hertz experiment — J. Franck & G. Hertz 1914

levels via collisions





Electrons from a hot cathode K are accelerated toward grid G through mercury vapour. A small retarding voltage stops slow electrons from reaching anode A.

Anode current vs accelerating voltage (schematic of the 1914 curve): drops every 4.9 V, each time electrons gain enough energy to excite one more Hg atom.

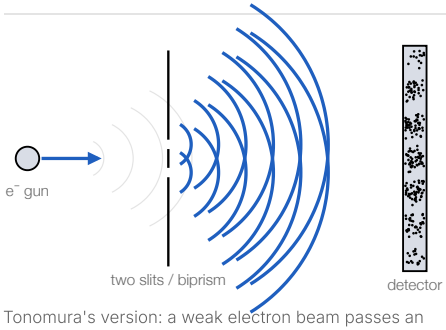
Classical Electrons should lose energy to atoms in any amount, so current rises smoothly with voltage.

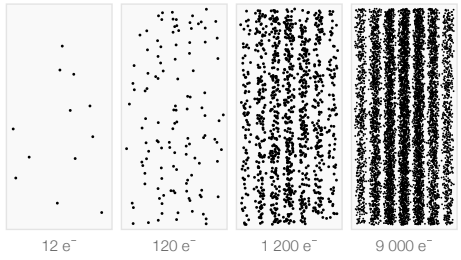
Observed Sharp current drops at 4.9 V spacing; the vapour then glows at 254 nm $= hc/4.9$ eV.

Lesson Discrete levels show up in collisions too, not just in light: atoms accept energy only in fixed amounts.

6 Double slit with single electrons — Davisson–Germer 1927 · Jönsson 1961 · Tonomura 1989

amplitudes & Born rule





Tonomura's version: a weak electron beam passes an electron biprism (equivalent to two slits). A position-sensitive detector records each arrival as a dot.

Build-up of arrivals (simulated from the interference law, as in Tonomura's frames). Each dot is random; the pattern emerges only statistically.

Classical Particles go through one slit or the other: two overlapping bumps. Waves would arrive spread out, not as dots.

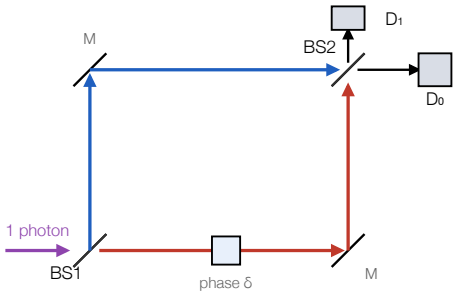
Observed Single dots, one at a time, building fringes with spacing $\lambda L/d$, $\lambda = h/p$. Davisson–Germer: 54 eV electrons on nickel diffract at 50°, matching $\lambda = 1.67$ Å. Determining which slit erases the fringes.

Lesson Amplitudes add, then square (Born rule); outcomes are random; which-path information destroys interference. Seen with neutrons, atoms, even C_{60}.

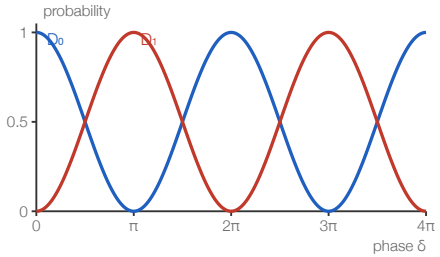
$$P(x) = |\psi_1 + \psi_2|^2 = |\psi_1|^2 + |\psi_2|^2 + 2\,\text{Re}\,\psi_1^*\psi_2$$

7 Single-photon Mach–Zehnder — Grangier, Roger & Aspect 1986

superposition of paths



One photon at a time: beam splitter BS1, two mirrors, a phase shifter δ in one arm, recombining splitter BS2 and detectors D_0, D_1.



Detection probabilities vs phase δ: full-contrast fringes even with single photons. With only BS1, the two outputs never fire together (anticorrelation $\alpha = 0.18 \ll 1$).

Classical A particle takes one arm (no interference); a wave splits and could trigger both detectors at once.

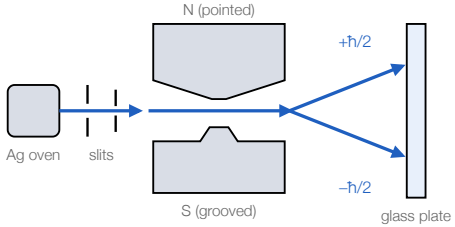
Observed At one splitter the photon is found on one side only, yet in the full interferometer the two paths interfere.

Lesson The photon is in a superposition of paths, and relative phases are physical. Elitzur–Vaidman: a live bomb in one arm is found without being touched (¼ of the time; near 100% with the Zeno trick).

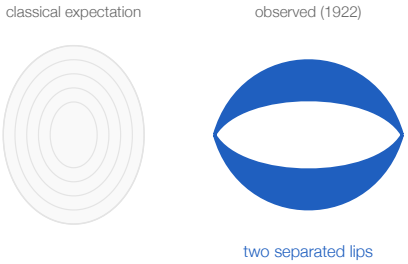
$$P(D_0) = \cos^2\frac{\delta}{2}, \qquad P(D_1) = \sin^2\frac{\delta}{2}$$

8 Stern–Gerlach — O. Stern & W. Gerlach 1922

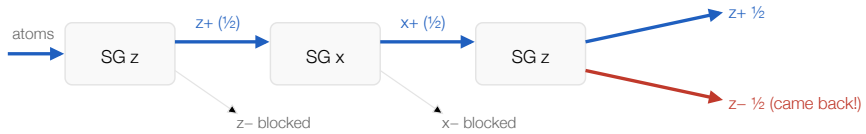
spin & measurement



Silver atoms from an oven pass a magnet with one pointed pole, which makes a strong field gradient: force $F_z = \mu_z \partial B_z/\partial z$.



The deposit on the glass plate: classically a continuous smear; observed, two separate "lips" (Gerlach's famous postcard to Bohr).



Sequential analysers: after selecting $z+$ and then $x+$, a final z measurement gives $z-$ half the time. The x measurement erased the z information.

Classical Atomic magnets point in random directions, so deflections should be continuous.

Observed Exactly two outcomes, along any axis you choose.

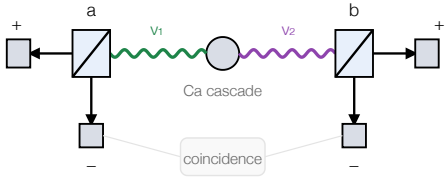
Lesson Intrinsic spin ½ (a two-state system); quantized angular momentum; measurement changes the state; S_x and S_z are incompatible.

$$|z;+\rangle = \tfrac{1}{\sqrt{2}}\big(|x;+\rangle + |x;-\rangle\big), \qquad [\hat{S}_x, \hat{S}_z] = -i\hbar\hat{S}_y \neq 0$$

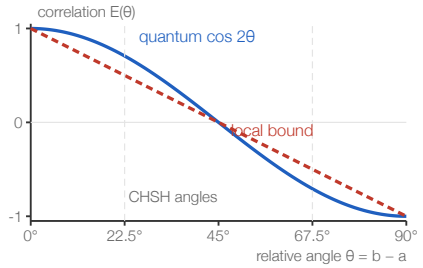
9 Bell tests

EPR 1935 · Bell 1964 · Aspect, Grangier & Roger 1982 · loophole-free 2015

entanglement



Calcium atoms emit polarization-entangled photon pairs in opposite directions. Each side has a two-channel polarizer at angle a or b; coincidences are counted.



Correlation vs relative angle: quantum $E = \cos 2\theta$ (blue) vs the best local hidden-variable model (red). Measured: $S = 2.697 \pm 0.015$ (Aspect 1982), QM predicts 2.70.

Classical EPR: perfect correlations mean outcomes were fixed in advance by local hidden variables. Then the CHSH combination $S \leq 2$.

Observed $S \approx 2.7$, violating the bound by tens of standard deviations. 2015 experiments (Delft, NIST, Vienna) closed the locality and detection loopholes; Nobel 2022.

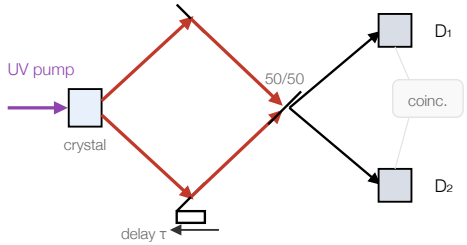
Lesson Nature is not locally realistic. Entanglement is a resource (teleportation, QKD) but still can't send signals faster than light.

$$S = |E(a,b) - E(a,b') + E(a',b) + E(a',b')| \leq 2 \ \text{(local)}, \qquad S_{\text{QM}}^{\max} = 2\sqrt{2}$$

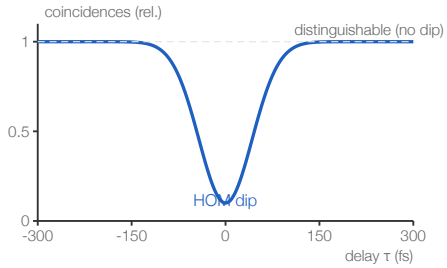
10 Hong–Ou–Mandel

C. K. Hong, Z. Y. Ou & L. Mandel 1987

identical particles



A UV pump in a nonlinear crystal makes twin photons. They meet at a 50/50 beam splitter from opposite sides; a movable mirror sets their relative delay τ.



Coincidence rate vs delay: it drops nearly to zero when the photons arrive together (the "HOM dip"). The dip width is the photons' coherence time, ~100 fs.

Classical Two independent particles exit on opposite sides half the time.

Observed Identical photons arriving together always leave by the same port.

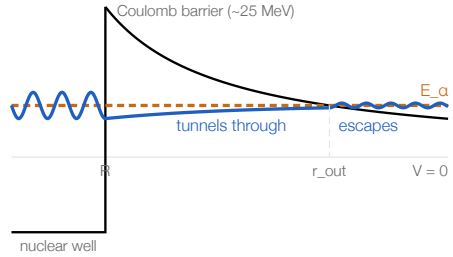
Lesson "Both transmitted" and "both reflected" are indistinguishable and their amplitudes cancel. Bosons bunch; fermions would always separate (Pauli).

$$A_{\text{coinc}} = t^2 + r^2 = \left(\tfrac{1}{\sqrt{2}}\right)^2 + \left(\tfrac{i}{\sqrt{2}}\right)^2 = 0$$

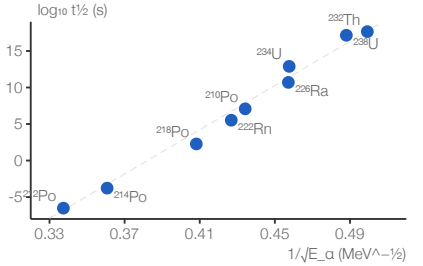
11 Alpha decay

Geiger & Nuttall 1911 · Gamow, Gurney & Condon 1928

tunneling



The α particle sits in the nuclear well below the top of the Coulomb barrier. Its wavefunction oscillates inside, decays through the barrier, and leaks out.



Real half-lives vs $1/\sqrt{E_\alpha}$: a factor of 2 in energy changes the half-life by 24 orders of magnitude, just as tunneling predicts.

Classical An α particle with 4–9 MeV can never cross a ~25 MeV Coulomb barrier.

Observed Nuclei emit α particles with half-lives from 10^{-7} s to 10^{17} s, and $\log \tau$ is linear in $Z/\sqrt{E}$ (Geiger–Nuttall).

Lesson Wavefunctions penetrate classically forbidden regions with exponential sensitivity. Same physics: scanning tunnelling microscope, fusion in stars.

$$T \sim e^{-2\theta}, \quad \theta = \frac{1}{\hbar}\int_R^b \sqrt{2m(V-E)}\,dr \ \Rightarrow \ \ln \tau \approx a + \frac{bZ}{\sqrt{E}}$$

+ Further confirmations

- **Aharonov–Bohm** (1959; Tonomura 1986): electron fringes shift around a shielded solenoid where $\vec{B} = 0$, so potentials and phases are physical.
- **Lamb shift** (1947) and electron $g - 2$: tiny shifts that need quantum fields (QED).
- **Zeeman & fine structure:** spin–orbit coupling, $g = 2$, relativistic corrections.
- **Quantum Zeno effect** (Itano 1990): frequent measurement freezes a transition.
- **Decoherence** (Haroche 1996): a cavity "cat state" observed losing coherence, showing why the everyday world looks classical.

What each experiment forces on the theory

Principle	Forced by	Sheet
Quanta: $E = \hbar\omega$, $p = \hbar k$	1 Blackbody · 2 Photoelectric · 3 Compton	8.04 §3
Discrete bound-state energies	4 Spectra · 5 Franck–Hertz	8.04 §9–17
Matter waves $\lambda = h/p$	6 Davisson–Germer	8.04 §3–4
Complex amplitudes add; superposition	6 Double slit · 7 Mach–Zehnder	8.04 §1–2
Probability $= \lvert\psi\rvert^2$; randomness	6 Single-electron build-up	8.04 §5
Measurement disturbs; incompatible observables	8 Stern–Gerlach sequences · 6 which-path	8.04 §7 · 8.05 §5
Spin ½; quantized angular momentum	8 Stern–Gerlach	8.05 §2, §9
Entanglement; no local realism	9 Bell tests	8.05 §8
Indistinguishable particles	10 Hong–Ou–Mandel	8.06 §8
Tunneling	11 Alpha decay	8.06 §4

> **The minimal set.** Photoelectric (quanta) + Franck–Hertz (levels) + single-electron double slit (amplitudes, Born rule, complementarity) + Stern–Gerlach sequences (spin, measurement, non-commutation) + a Bell test (entanglement) together demand every axiom of quantum mechanics. Exchange symmetry needs Hong–Ou–Mandel as well.