

THE IN A HURRY SERIES

Quantum *in a Hurry*

The strange rules of the very small

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The Whole Thing in One Page

Quantum physics is famous for things that seem impossible: particles behaving like waves, distant objects sharing a state, a cat both alive and dead. The reputation hides a stricter subject. Quantum theory predicts what happens when a physical system is prepared, allowed to evolve and measured. Its rules are strange because they depart from familiar objects, not because they permit arbitrary events. The same framework that unsettles our picture of reality explains why atoms persist and materials have dependable properties.

The first change is in how possibilities combine. Send electrons one at a time through an arrangement with two coherent routes. Each detection is local, yet the accumulated pattern contains interference. Quantum theory attaches amplitudes, with magnitude and phase, to the alternatives. It combines those amplitudes before calculating probabilities. Contributions can cancel. An ordinary lottery over two unchanged routes cannot do that. A superposition retains phase relationships which the next operation can reveal.

Confinement selects allowed patterns. An atom's bound states have only certain definite energies, just as a fixed string has only certain standing-wave modes. Superpositions of the corresponding states remain possible. Transitions between energy levels produce sharp spectral lines, while the lowest state gives an atom stability. This does not make every quantity discrete: free-particle energies and position can have continuous ranges. Quantisation depends on the system and the question.

Measurement supplies that question physically. A spin analyser selects an axis; changing it changes the possible predictions for the same preparation. Some quantities cannot both have arbitrarily narrow distributions in one state. Position-momentum uncertainty expresses this constraint rather than a defect in microscopes. Between measurements, the energy operator determines how the state evolves. The theory can predict a whole distribution precisely without selecting the next individual result.

Putting particles together introduces another rule. Identical electrons cannot be assigned distinguishable identities merely by labelling them. Their exchange symmetry produces Pauli exclusion, which prevents duplicate occupation of a full single-particle state. Electron shells and resistance to compression follow in combination with electromagnetic forces. Bosons obey a different symmetry and can share states. Tunnelling adds another departure: a finite barrier can transmit a particle which lacks the energy to cross it classically, without any temporary violation of energy conservation.

Entanglement gives a joint state more structure than independent descriptions of its parts. Bell experiments test correlations across different detector settings. Their violations exclude the relevant local hidden-instruction accounts under stated assumptions, including independence of the settings from the source. They do not provide a faster-than-light communication channel or disprove every theory with an underlying reality.

The environment then changes what can be observed locally. Interactions spread correlations into surrounding matter and radiation, making interference between familiar alternatives inaccessible. This decoherence helps explain durable records and classical appearance. It does not by itself select one outcome from a globally evolving state. Interpretations address that remaining problem differently.

The small is where these rules are easiest to expose, not where their authority ends. Ordinary matter already depends on them. Keeping interference visible requires control; obtaining a stable record usually requires letting that delicate coherence go.

That is the book.

Why You Should Care

Every second of your life depends on an electron failing to fall into an atomic nucleus.

Classical physics cannot give a stable atom of the familiar kind. A charge

following a classical orbit should radiate, lose energy and collapse towards the nucleus. The quantum atom instead has a finite ground state. Confining the electron more tightly broadens the momenta needed to describe it and raises the kinetic energy. Attraction pulls inward; quantum structure resists indefinite collapse. The result is not a decorative microscopic correction. It is the existence of atoms.

Once atoms have structure, the rest follows outward. Quantised energy differences give elements their spectral fingerprints. Electron spin and Pauli exclusion organise shells, which organise the periodic table, which organises chemistry. Bonds hold proteins, membranes, metals and rocks together. The feel of a tabletop emerges from electromagnetic interaction acting through quantum states that identical electrons are permitted, or forbidden, to occupy.

The Sun needs the theory too. Positively charged nuclei in its core usually lack enough classical energy to overcome their mutual electric repulsion. Tunnelling gives some pairs access to the short distances required for fusion. The rate also depends on nuclear reactions, including a slow weak-interaction step. Tunnelling is indispensable to that account, not an explanation of fusion by itself.

Then the devices. Semiconductors work because electrons in crystals occupy quantum bands. Lasers depend on quantised transitions and stimulated emission. Atomic clocks count frequencies fixed by quantum energy differences. Magnetic resonance, superconducting circuits and scanning tunnelling microscopes all use rules that sound like paradoxes when detached from their apparatus. Modern life is not surrounded by quantum effects. It is assembled from them.

Even colour carries the signature. In a pigment, some photon energies are absorbed while others survive to reach your eye. A light-emitting screen produces photons instead. The mechanisms differ, but both depend on the states available to electrons in matter. Energy levels are something you can look at before learning to calculate them.

That practical success makes the conceptual trouble harder to dismiss. Quantum mechanics predicts experiments with exceptional accuracy while defeating the ordinary picture of objects carrying a complete, locally determined inventory of values. A state can evolve smoothly, then yield one of several records. The question chosen by an apparatus matters to which values can appear. Entangled systems violate Bell inequalities while withholding any faster-than-light signal. Physicists agree on the predictions and still dispute what the formalism says exists.

This is a rare intellectual situation. The theory is not unfinished because it performs badly. It is troubling because it performs so well. More than a century of increasingly controlled experiments has tightened the constraints on any comfortable replacement. Hidden local answer sheets fail. Consciousness is not needed to make detectors work. “Anything can happen” is false. The mystery survives after the easy escapes are removed.

The vocabulary can betray you. Particle, wave, observation and uncertainty arrive from ordinary life carrying assumptions the equations do not honour. A loose metaphor can turn a precise result into nonsense. Ask what was prepared, what remained coherent and what was measured: those questions keep the words attached to an experiment.

You do not need to choose an interpretation before understanding an experiment. Nor do you need quantum algorithms, a tour of competing computers or a shelf of miracle products with quantum on the label. Those are different subjects, and the products may have no subject at all. What you need is a working model of the rules, with enough mathematics to see what they demand.

The reward is a world that becomes stranger in the right places. Atoms are stable because confinement has a price. Matter has shape because particles cannot always share a state. Barriers leak, wholes possess irreducible correlations, and environmental interaction helps turn quantum possibilities into the stable records of everyday experience.

The Core Ideas

Amplitudes change how possibilities combine

Send electrons towards a screen one at a time, through two narrow openings. Each arrival leaves a local mark. After enough arrivals, the dots form alternating bands of high and low density. Close one opening and the two-path fringes disappear, although the remaining slit can still produce diffraction. Something about having two coherent routes changes where even a single electron can arrive.

An ordinary mixture of two unchanged, independent routes cannot explain that pattern. Its probabilities add: arrivals from the left route plus arrivals from the right. The sum cannot cancel either contribution. Quantum mechanics uses a different rule. Each route contributes a probability amplitude, a number with a magnitude and a phase. The amplitudes add first. The Born rule then converts their combined magnitude into a probability by squaring it. Cancellation is possible before the probability is calculated.

To see the difference without a screen full of dots, consider an idealised, balanced, lossless interferometer with two routes and two output detectors. The apparatus splits and recombines a particle's state. Suppose the two routes each contribute an amplitude of $+1/2$ to one output. Their sum is 1, giving probability 1. Change the phase of one route so that its contribution is $-1/2$. The sum becomes zero, giving probability zero at that output. The particle is then certain to leave by the other output. No probability has vanished; the apparatus has redistributed it.

The minus sign is a simple case of phase. More generally, an amplitude can be represented by an arrow in a mathematical plane. Its length gives the magnitude; its angle gives the phase. Arrows pointing together reinforce one another, while opposed arrows cancel. The arrow is not a tiny object rotating inside the electron. It is a way of keeping track of the complex numbers whose combination predicts detector counts.

Superposition names a state containing such coherent alternatives. In the two-route experiment, changing the relative phase changes the result when the routes reunite. Merely being uncertain which route a classical object took does not provide this extra structure. Two preparations can give identical fifty-fifty statistics when measured separately along the routes, yet give opposite outcomes after recombination. To describe them as the same coin toss would discard something the next measurement can detect.

A path detector changes the calculation. It correlates the routes with different states of another system. Once those states distinguish the paths completely, the electron's local interference disappears, even if nobody reads the detector. The combined electron-detector state still has quantum structure, but ignoring the detector is no longer equivalent to recombining two unmarked routes. Partial marking gives an intermediate loss of contrast.

Carefully reversing the marking interaction can restore the original coherence. Deleting a stored file cannot. In a different procedure called quantum erasure, suitable measurements of the marker allow the detections to be sorted into subsets showing complementary interference patterns. Pool the subsets and the fringes cancel. The later sorting does not rewrite an earlier detector record or send information backwards through time.

Wave and particle each describe part of this behaviour. Wave language captures phase and interference; particle language captures local exchanges. Neither is an adequate classical picture of the whole experiment. Quantum mechanics supplies a state, a rule for changing it, and probabilities for the measurement chosen. The test of that account is not whether the electron resembles a familiar object. It is whether changing the apparatus moves the counts by the predicted amount.

Confinement turns continua into allowed patterns

Pluck a guitar string and you hear a note with overtones, not one perfectly pure frequency. Its motion combines standing-wave modes, each fitting a whole number of half-wavelengths between the fixed ends. Complex motion is allowed; arbitrary mode frequencies are not. The endpoints set the terms before the guitarist gets a say.

Quantum confinement imposes a related demand, though the constrained object is a quantum state rather than a material string. For an electron bound to a nucleus, a state of definite energy must have a wavefunction that fits the potential and gives a finite total probability. Only certain energies satisfy those conditions. They form a ladder, and a transition between rungs transfers a definite amount of energy. The electron may also occupy a superposition of these states: the ladder restricts the results of an energy measurement, not every possible preparation.

This is quantisation in its most useful form. It does not mean every physical quantity everywhere comes in indivisible pellets. A free particle can have a continuous range of energies. Position is usually treated as continuous in standard quantum mechanics. Discreteness often appears when a system is bound, periodic, rotating or otherwise constrained. The allowed answers are selected by the structure of the problem.

Atomic spectra made that structure visible before physicists understood it. Excited hydrogen emits light at sharply defined wavelengths rather than every colour. Nineteenth-century spectroscopists measured the lines and found numerical patterns. Bohr's 1913 atom imposed selected electron energies and explained the hydrogen frequencies by differences between them. His orbit picture was temporary, but the energy ladder survived. Modern quantum mechanics replaced paths around the nucleus with orbitals, standing patterns in three dimensions labelled by quantum numbers.

An orbital is not a planetary track. It is a state with a spatial probability distribution, energy and angular structure. The familiar shapes drawn in

chemistry books are surfaces around regions where a chosen fraction of the electron probability lies. Nodes are places where the wavefunction vanishes; real orbitals often change sign across them. They matter because phase and geometry govern overlap, transitions and bonding.

Confinement also repairs a fatal classical problem. An accelerating electric charge should radiate, so a classical electron orbiting a nucleus would lose energy and spiral inward. Quantum mechanics supplies a lowest-energy state. The electron does not sit motionless inside the nucleus; a state squeezed into a smaller region requires a broader spread of momentum. The uncertainty relation makes indefinite compression costly. Attraction lowers the energy as the electron comes closer, while confinement raises its kinetic contribution. Their balance gives the atom a finite scale.

Electrons in a crystal occupy bands formed from vast numbers of overlapping atomic states. A nanometre-scale structure can shift colour because tighter confinement changes its energy levels. Rotational and vibrational states give molecules their spectral fingerprints.

A harmonic oscillator supplies another anchor. Classically it can rest with zero energy. Quantum mechanically its lowest state retains zero-point energy because a state with exactly fixed position and momentum is unavailable. Molecular vibrations, lattice motion and field modes inherit versions of this ladder. Quantisation is therefore tied to the permitted modes of motion, not to matter being chopped into universal cubes.

A measurement asks a physical question

In 1922, Otto Stern and Walther Gerlach sent a beam of silver atoms through a non-uniform magnetic field. Classical reasoning suggested a smear on the receiving plate. The atoms' magnetic orientations might point at every angle, so the force should vary continuously. The beam split into two.

The historical apparatus was understood fully only after electron spin entered the theory. Its enduring lesson is that a measurement is not a neutral camera pointed at a property that already has a classical value. An

apparatus is built to couple to a particular observable, and the observable defines the set of outcomes it can record. For the relevant component of angular momentum, the silver atoms supplied two alternatives.

Consider an idealised sequence of spin analysers. Prepare spin-up along the vertical axis and test it vertically again: up returns with certainty. Test instead along a horizontal axis: up and down each have probability one half. Select the horizontal-up output and test that group vertically. Up and down are now equally likely. These are predictions for repeated preparations, not instructions to follow one particle whose full future has been recorded. The intermediate measurement prepares a state definite for a different question.

The terminology becomes easier once it has an apparatus to attach to. Quantum theory represents an observable by an operator, a mathematical rule acting on the state. In our vertical spin test, its eigenvalues are the two possible readings. A vertical-up state is an eigenstate: it gives one reading with certainty. The vertical-up and vertical-down states form a measurement basis, the alternatives in which we express the preparation. The Born rule turns their amplitudes into probabilities. Turn the analyser sideways and the same preparation has different components in the new basis.

Vertical-up is a pure state even though a horizontal test is unpredictable. Pure does not mean certain in every measurement. A mixed preparation additionally involves probabilities over pure states, as when an apparatus randomly prepares vertical-up or vertical-down. In an ideal repeatable test, selecting one result prepares the corresponding state. Test it again immediately, without a change in between, and the answer repeats. Measurement need not destroy the particle.

A basis is therefore part of the question, not clerical notation added afterwards. Statements such as “the particle has no definite spin” are incomplete unless the component is named. The vertical-up preparation has a definite answer vertically and a spread of answers horizontally. Nothing about the particle has become contradictory; two different questions have been asked.

The uncertainty principle follows from the same structure. Position and momentum are represented by operators that do not commute: applying them in different orders is not equivalent. Their probability distributions cannot both be arbitrarily narrow in one state. The familiar relation sets a lower bound on the product of their standard deviations. This is not a complaint that microscopes kick particles too hard, though measurements can cause disturbance. Even a perfectly prepared state has the trade-off. A narrow wavepacket in position requires many wavelengths, and therefore many momenta, to build it.

Uncertainty does not make prediction useless. Quantum mechanics often predicts distributions with extraordinary precision, and it can predict some outcomes with certainty. What it refuses is a classical package in which every possible measurement has a simultaneously sharp value of the familiar kind. Which quantities can be definite together depends on their algebra.

Nor does measurement require a mind. A photographic plate, ionisation chamber or superconducting amplifier can create a durable record before anyone reads it. The remaining foundational question is how the formal possibilities relate to the one outcome an observer experiences.

Interpretations answer that differently. Laboratory practice does not wait for agreement: prepare the state, specify the observable, model the interaction, and count the records.

The particle has not become forgetful. The analyser changed the question and, when an outcome was selected, the preparation for the next test.

Identical particles make matter possible

Two classical coins can look identical while remaining coin A and coin B. Paint one invisibly, follow their paths, and the labels still make sense. Fundamental particles of the same species are identical in a stronger way. There is no hidden serial number by which one electron can be distinguished from another electron. Exchanging them cannot create a new physical arrangement merely because the labels in our calculation changed.

For familiar particles in three spatial dimensions, quantum mechanics enforces that fact through symmetry. Swap two identical particles and the joint wavefunction behaves in one of two main ways. For bosons it stays the same. For fermions it changes sign. The minus sign has no direct effect on a single probability, but it makes a decisive state impossible: two identical fermions cannot occupy the same one-particle quantum state. If the proposed state is unchanged by swapping the particles and must also change sign, it can only be zero.

That is the Pauli exclusion principle. Electrons are fermions, so a spatial atomic orbital can hold at most two electrons, with opposite spin states. The full one-particle state includes spin. As protons are added to a nucleus, electrons cannot all collapse into the lowest orbital. They fill a hierarchy of states. The resulting shell structure underlies the recurring pattern of chemical behaviour organised by the periodic table. Chemistry inherits its architecture from the exchange symmetry of particles that cannot be told apart.

Exclusion also helps ordinary matter occupy space. Compress many electrons into a smaller region and available low-energy states fill. Further electrons must take states with larger momenta, raising the energy and pressure. Electromagnetic attraction and repulsion, quantum kinetic energy and nuclear structure all participate in the stability of matter. Saying that a table feels solid only because of Pauli exclusion is too neat. Contact forces emerge from the joint quantum and electromagnetic behaviour of enormous assemblies. Exclusion is one load-bearing rule in that account.

Fermionic statistics shape dense stars as well. In a white dwarf, electron degeneracy pressure can resist gravitational compression up to a limit. In a neutron star, related quantum pressure and nuclear interactions matter. These are not tiny laboratory curiosities. A rule about exchanging indistinguishable particles helps decide which dead stars can support themselves.

Bosons follow the other symmetry. Multiple bosons may occupy the same state, allowing collective behaviour such as Bose-Einstein condensation.

Photons are bosons, and stimulated emission can add photons matching an existing mode, one ingredient in laser operation. Superfluidity and superconductivity involve collective quantum states, though the microscopic details differ and cannot be reduced to the word boson alone.

Particle identity also changes counting. With distinguishable objects, swapping occupants between boxes can produce a new arrangement. With identical quantum particles, some of those apparent arrangements are the same physical state, while fermionic alternatives can cancel. Statistical mechanics must therefore use Bose-Einstein or Fermi-Dirac statistics where quantum overlap matters, rather than classical counting.

The periodic table, the resistance of matter to compression and the light from a laser look like separate subjects. Quantum identity joins them. Matter is organised by forces acting between particles and by the rules governing what counts as a different many-particle state.

A forbidden region can still be crossed

A classical ball with too little energy to climb a hill turns back. Draw its energy as a horizontal line below the top of a barrier and the verdict is final. The region beyond may exist, but the ball cannot reach it without extra energy.

A quantum state does not end sharply at the classical turning point. In a simple opaque barrier, the transmitted amplitude is exponentially suppressed with increasing barrier width. If the barrier is thin enough, the tail reaches the far side. A transmitted wave can then continue beyond it. Repeated trials produce some reflected particles and some transmitted particles even when every particle has less energy than the barrier height.

This is tunnelling. The language invites bad explanations. The particle does not borrow energy and repay it before an auditor notices. Energy conservation remains in force. Nor is the barrier briefly absent. The quantum solution to the full boundary problem has a non-zero amplitude on the far side. “Classically forbidden” means the classical trajectory assigns zero access, not that quantum mechanics suspends its own rules.

The probability is acutely sensitive to thickness, barrier height and particle mass. Small changes can alter the transmission rate by orders of magnitude because the amplitude decays exponentially inside the barrier. That sensitivity turns tunnelling into both a natural clock and a measuring tool.

Alpha decay is a natural example. The nuclear attraction holds an alpha particle in a potential well, separated from the outside by an electric barrier. The released alpha particle has positive kinetic energy outside but insufficient energy to pass classically over the barrier. Quantum mechanics permits escape through it. George Gamow and, independently, Ronald Gurney and Edward Condon used this mechanism in 1928 to explain why modest differences in alpha energy can accompany enormous differences in decay rate.

Stars also depend on penetration of an electric barrier. In the Sun's core, the thermal distribution gives some protons more energy than others, but classical over-the-barrier encounters would be far too rare to explain the observed fusion rate. Tunnelling greatly increases the chance of close approach. It is not the whole reaction: in the proton-proton chain's first step, the weak interaction must also convert a proton into a neutron, allowing a deuterium nucleus to form. That additional slow process helps explain why the Sun burns steadily rather than exhausting its fuel at once.

The scanning tunnelling microscope turns the same rule into an image. Bring a conducting tip within roughly a nanometre of a surface and apply a voltage. Electrons tunnel across the gap, producing a current that changes steeply with distance and the local electronic structure. Move the tip while keeping current controlled and the instrument maps surfaces with atomic-scale resolution. The picture is an inference from tunnelling current, not a photograph of hard spheres.

Tunnel junctions appear in electronics, superconducting devices and nuclear physics. They also expose a wider correction. Quantum mechanics does not divide events into the possible and impossible at the same boundary as classical mechanics. It supplies amplitudes, and some classical zeros become small but calculable probabilities.

The barrier's shape matters as much as the word tunnelling. An electron crossing a narrow vacuum gap and an alpha particle escaping a nucleus face different potentials, masses and available energies. A person passing intact through a wall is not either problem enlarged. Treating a warm, interacting body as one isolated particle would discard the conditions the calculation requires. The useful lesson is narrower: a classical turning point need not be a hard edge to a quantum wavefunction.

A whole can have facts its parts do not possess

Prepare two spin-one-half particles in a singlet state. The pair has total spin zero. Measure both along the same axis and the results are always opposite. Yet before either measurement, quantum theory does not assign each particle a separate, definite spin value along every possible axis. The clean fact belongs to the pair.

Ordinary objects can be correlated too. Put one left glove and one right glove in separate boxes, then send them apart. Opening one box reveals what the other contains. Nobody needs to alert the distant glove. Its handedness was fixed before the boxes left. A local hidden-variable account tries to extend that idea: each quantum particle leaves the source with hidden instructions specifying the result for every possible detector setting.

Entanglement goes beyond ordinary shared preparation. For a pure joint state, no separate state for each part reproduces the whole. Allowing random mixtures of independent preparations gives a broader test: a joint state is entangled only if that still cannot describe it. The distinction prevents every pair with a common history from qualifying as entangled. Correlation alone is cheap; the quantum claim demands more.

Einstein, Boris Podolsky and Nathan Rosen argued in 1935 that quantum predictions, combined with their conditions for locality and physical reality, implied an incomplete description. Existing experiments had not forced a choice between the quantum state and a deeper local account.

John Bell made the conflict testable in 1964. His local causal model allows shared information from the source, but each outcome depends only on that

information and its own detector setting, not on the distant setting or result. The settings must also be statistically independent of the hidden source information. Together these assumptions limit the correlations across different settings. Quantum mechanics predicts violations. The difference is experimental, not a matter of taste.

Tests beginning with Stuart Freedman and John Clauser in 1972, followed by Alain Aspect and colleagues in 1982, found the quantum pattern. Experiments in 2015 closed the major detection and locality loopholes together in separate systems, subject to the statistical and physical assumptions any such test requires. The comfortable model in which separated particles carry local answer sheets for every setting cannot reproduce the observed correlations.

Bell violation is often translated into faster-than-light messaging. That does not follow. For the singlet, each local spin result is an unbiased random outcome. More generally, the no-signalling rule says that changing the distant measurement cannot change the probabilities visible in the local record alone. The correlation appears when both records are compared through an ordinary communication channel. The distant researcher cannot tell from those local counts which setting you chose. That is why the correlation cannot carry your message.

Bell nonlocality therefore does not mean that experiments have observed a controllable instantaneous force. It means the correlations violate the relevant local causal constraints. Theories can reject different assumptions in that package, at different costs. Bohmian mechanics, for example, retains definite particle configurations but gives up Bell locality.

Perfect opposition along a shared axis would not establish this result: gloves already provide perfect correlation. The decisive feature is the pattern obtained when the axes differ. No single collection of local advance answers can satisfy all those quantum correlations together. Entanglement and Bell violation are consequently not synonyms. Some entangled states do not violate a given Bell test; the test and the state both matter.

Entanglement shows that separability, the assumption that every whole can be reduced to independently possessed facts of its parts, is not a universal rule. Sometimes the most definite property in the experiment belongs nowhere smaller than the pair.

The environment makes interference inaccessible

Schrödinger's cat was designed to expose a difficulty, not to report an animal experiment. In his 1935 thought experiment, a microscopic event controls a poison-releasing device. Let the wave equation govern the complete arrangement, and the alternatives become correlated: decay with a released poison, no decay with a surviving cat. The calculation contains different outcomes. Experience supplies a definite record. What connects them?

A real cat is not the isolated object that a simple drawing suggests. It exchanges radiation with its surroundings and collides with air molecules. Its internal activity also links countless degrees of freedom. Those interactions matter even when the lid is closed and nobody looks inside. To understand the record, the calculation must include something beyond the animal and the radioactive nucleus.

Consider instead an idealised dust grain with two separated position alternatives. Light scattered from one position can differ from light scattered from the other. The grain becomes entangled with those photons. If we continue to describe the total system by ordinary quantum evolution, its coherence has not been annihilated. But a measurement of the grain alone no longer has access to the phase relations now carried in correlations with its surroundings. Interference between the positions is suppressed.

This is decoherence. The grain's reduced state gives local probabilities resembling a mixture of ordinary alternatives. It does not follow that the total state has secretly chosen one of them. Confusing those two statements turns a successful physical mechanism into an unsupported solution of the measurement problem. The mechanism explains why the interference becomes inaccessible; an account of definite outcomes needs a further

interpretive or dynamical step.

The interaction also favours some records over others. Position information can be repeatedly scattered into light without substantially shifting a heavy object's location. Such robust alternatives are called pointer states. Their persistence helps explain why many observers can consult the same apparently classical object rather than each creating an unrelated description. An instrument's pointer and an entry in its memory become useful precisely because subsequent interactions tend to preserve the recorded distinction.

Size affects the difficulty of preserving coherence, but it is not a prohibition. Large systems often have many efficient channels for environmental coupling. Carefully controlled collective states in superconductors and superfluids nevertheless display quantum behaviour across many particles. Interference experiments can also preserve selected alternatives of a composite object's centre-of-mass motion. They need not freeze every internal motion or make the whole object one featureless quantum degree of freedom.

The familiar trajectories of a thrown ball require more than suppressed interference. The state must remain suitably concentrated, the forces must vary smoothly on its spread, and the resolution of interest must permit a classical approximation. Quantum mechanics then recovers Newtonian predictions to the required accuracy. A poorly isolated object need not behave as a neat classical point; decoherence is one part of the explanation, not a universal recipe for every classical law.

In the two-route experiment, the alternatives could interfere because nothing else distinguished them. A reliable physical record of the route suppresses those local fringes whether anybody reads it or not. Ignoring the record does not cause the change; the interaction that made the record does. The same capacity for forming quantum correlations that makes entanglement possible also makes interference hard to retain in everyday objects.

Copenhagen-style accounts use a measurement rule or a classical

description of apparatus. Many-worlds approaches retain unitary evolution and analyse the different records as decohered branches. Bohmian mechanics adds definite configurations guided by the wavefunction. Objective-collapse theories alter the dynamics and can make different experimental predictions. Decoherence constrains all these discussions, but does not turn any one account into the measured conclusion. The solid world becomes less surprising without pretending that the question raised by the cat has disappeared.

How It Actually Works

A furnace breaks the old physics

In Berlin in 1900, Max Planck faced a precise mismatch between a successful formula and the light leaving a hot cavity. Wien's radiation law worked well at short wavelengths; improved measurements showed it failing at longer ones. Planck found a formula that fitted both regimes. In December, seeking its statistical basis, he divided the energy of idealised material oscillators into elements proportional to their frequency. The proportionality constant became h .

A furnace changes from red towards white as it heats, but it does not radiate equally at every wavelength. Explaining the distribution meant explaining how matter and radiation shared energy. Planck's counting procedure departed from unrestricted continuous exchange, without yet supplying Einstein's later picture of independent light quanta. The enduring relation was $E = hf$: frequency f multiplied by Planck's constant gives the energy element. The new physics began with a measured spectrum that existing reasoning could not fit.

Albert Einstein made the proposal harder in 1905. He argued that, in some interactions, light itself behaves as localised energy quanta. The photoelectric effect gave the idea a test. In the ordinary single-photon regime, shining more light of a fixed frequency on a suitable metal can release more electrons, but their maximum kinetic energy is set by the

frequency and the material's electron-removal energy. Below the threshold, increasing that light's intensity does not make one photon energetic enough. Strong-field, multiphoton processes are a different regime.

A later diagnosis showed how deeply the new radiation law departed from classical physics. Classical equipartition assigned comparable thermal energy to an unlimited number of high-frequency modes, driving the predicted radiated energy upward without bound. The measured spectrum instead peaked and declined. This became known as the ultraviolet catastrophe. The catastrophe explains the depth of the problem. The long-wavelength measurements explain why Planck tackled it when he did.

For the single-photon process, the energy balance is direct: hf pays the cost of removing the electron, and the remainder is its maximum kinetic energy. Raising frequency increases the payment per photon. Raising intensity increases the supply of photons.

The light quantum was resisted because electromagnetic waves already explained interference, diffraction and polarisation. Einstein had not replaced one failed theory. He had made a successful theory look incomplete. Robert Millikan's long photoelectric programme confirmed Einstein's linear frequency relation while Millikan remained cautious about the underlying light-quantum picture. Compton scattering in 1923 gave further evidence that radiation transfers energy and momentum in particle-like packets. The wave behaviour remained. Physics now had both halves and no classical object that could carry them comfortably.

The atom becomes a ladder

Atoms caused a second crisis. Their spectra were selective: sharp bright lines at some colours, or dark gaps where light had been absorbed. Ernest Rutherford's nuclear atom of 1911 concentrated positive charge in a small nucleus, but classical electrodynamics made orbiting electrons unstable. Niels Bohr's 1913 model allowed only selected orbits and required radiation to be emitted or absorbed when an electron jumped between them. It explained the hydrogen spectrum with striking accuracy.

Bohr's atom was an organised compromise. It used classical orbits, then forbade most of them by quantum rule. It worked best for hydrogen and could not supply a general mechanics. Yet it turned spectral lines into energy differences and made the stability problem impossible to ignore.

James Franck and Gustav Hertz supplied another direct pressure in 1914. Electrons accelerated through mercury vapour lost energy in repeated fixed amounts rather than across a smooth range. The atoms absorbed energy only when the electrons crossed the relevant excitation threshold, then emitted characteristic light on returning. The experiment did not validate every feature of Bohr's orbit picture, but it showed that atomic energy exchange had steps.

Experiments then revealed quantisation where no orbit picture helped. Stern and Gerlach's 1922 silver beam split into two in a non-uniform magnetic field. The result was first discussed through orbital angular momentum; after spin was proposed in 1925, the modern explanation centred on the unpaired electron's two spin outcomes. The apparatus had shown that a component of angular momentum did not vary continuously through every classical orientation.

Louis de Broglie reversed Einstein's move in 1924. If waves of light can appear as particles, perhaps particles of matter have wavelengths. He related wavelength to momentum. Clinton Davisson and Lester Germer later observed electron diffraction from a crystal, and George Paget Thomson observed electron diffraction through thin films. Matter produced wave patterns without ceasing to arrive in local detections.

The mechanics is rebuilt

Werner Heisenberg found one route in 1925 by refusing to picture electron orbits that no experiment could observe. He organised the measurable frequencies and intensities of atomic transitions into arrays of quantities. Max Born recognised the unfamiliar multiplication rule as matrix algebra, and with Pascual Jordan helped build matrix mechanics. The order of multiplication mattered, a feature that would become central to incompatible observables.

Erwin Schrödinger found a different route in 1926. Inspired by de Broglie, he wrote a wave equation whose stationary solutions reproduced atomic energy levels. The mathematics looked more visual than matrices: a wavefunction changed across space and time. Schrödinger initially hoped for a continuous physical wave account that would avoid quantum jumps.

Schrödinger's equation does more than list allowed atomic energies. Given a prepared state and the system's energy operator, called the Hamiltonian, it specifies how the amplitudes change with time. The Hamiltonian represents kinetic energy, potentials and interactions. For an isolated system, this unitary evolution preserves total probability. The Born rule is then used for the measurement chosen. A prediction needs both rules: how the state evolves, and how the evolved state produces outcome probabilities.

The two theories turned out to be equivalent formulations. Paul Dirac and others built a general transformation theory that showed how states and observables could be represented in different bases. Schrödinger's smooth waves and Heisenberg's tables of transitions were not rival physical mechanisms producing different answers. They were coordinate systems for one structure. What remained disputed was the meaning of the wavefunction.

Born supplied the rule that endured. The wavefunction itself does not give a material density of an electron spread like fog. Its squared magnitude gives the probability density for where a detection will occur. In a scattering

process, amplitudes determine the probabilities of different outcomes. For an isolated system, the state evolved deterministically, while the measurement rule assigned probabilities to possible records.

Heisenberg stated the uncertainty relation in 1927. Position and momentum could not both be assigned arbitrarily precise values within the new mechanics. His microscope argument emphasised measurement disturbance, but the mature relation is a property of quantum states and non-commuting observables. Bohr developed complementarity: experimental arrangements that reveal one aspect can exclude the conditions needed to reveal another. Their views were influential, though the label Copenhagen interpretation later covered a family of positions rather than one signed doctrine.

A stationary energy state supplies a useful test of the word wave. Its overall phase changes with time, but its position probabilities remain fixed: an atom need not visibly pulse merely because its wavefunction oscillates. In a superposition of different energies, the relative phases change at rates set by the energy differences. Later measurements can reveal those changes. The same link between energy and frequency that began with spectral lines now governs the timing of a controlled quantum experiment.

The 1927 Solvay conference became the emblem of the dispute. Einstein pressed Bohr with thought experiments designed to expose inconsistency or incompleteness. Bohr defended the framework. The exchanges did not reduce to one winner and one loser. Einstein accepted much of quantum theory's mathematics and contributed to it for years. He objected to treating the statistical state as a complete description of individual physical reality.

Identity, fields and the material world

Wolfgang Pauli introduced an exclusion rule in 1925 to organise atomic spectra: no two electrons in an atom could share the same full set of quantum numbers. Spin, proposed by George Uhlenbeck and Samuel Goudsmit and given a deeper relativistic treatment by Dirac, completed the shell account. Enrico Fermi and Dirac developed the statistics of particles subject to exclusion. Satyendra Nath Bose and Einstein supplied the contrasting statistics for particles able to share a state.

Bose and Einstein also predicted that a dilute gas of suitable particles could collect into one quantum state at low temperature. Dilute-gas atomic Bose-Einstein condensates were produced in 1995, long after the statistics were derived. The achievement made a coherent matter wave controllable across a cloud containing many atoms, another warning that quantum behaviour is limited by preparation and environment rather than by particle count alone.

These rules converted quantum mechanics from an atomic puzzle into the architecture of matter. Electron shells explained periodic chemical patterns. Band theory explained why solids conduct, insulate or behave as semiconductors. Quantum statistics explained heat capacities and collective states. The theory's strangeness was no longer confined to special experiments. It was supporting the ordinary material world.

Relativistic quantum theory brought another change. Dirac's 1928 electron equation joined quantum mechanics to special relativity and implied antimatter. Quantum field theory later treated particles as excitations of fields and allowed their creation and destruction. Its electromagnetic theory, quantum electrodynamics, made the interaction of matter and light calculable with extraordinary accuracy.

Measurements of atomic energy shifts and the electron's magnetic moment tested quantum electrodynamics through small, calculable corrections. Agreement required accurate experiments as well as a theory able to distinguish the leading effect from its refinements.

The change is larger than a better account of atoms. Nature's small objects are not permanent beads carrying a list of classical properties. Particle number itself may change. What persists is a rule-governed quantum state of fields and interactions.

The paradoxes are made testable

In 1935, Einstein, Podolsky and Rosen considered two systems that had interacted and then separated. Quantum theory allowed a measurement on one to predict with certainty the corresponding result for the other under the chosen arrangement. If distant actions could not alter physical reality here, they argued, then the second system seemed to possess a value not represented in the wavefunction. The wavefunction would be incomplete.

Schrödinger replied in the same year, introduced the term entanglement and devised the cat. His animal was not an attempt to persuade readers that cats hover indefinitely between life and death. It exposed the lack of a clear boundary between a microscopic superposition and a macroscopic record if the wave equation alone governed the whole chain.

Bell's 1964 theorem made a family of underlying explanations answerable to experiment. In 1969, John Clauser, Michael Horne, Abner Shimony and Richard Holt gave an especially useful formulation. Each side of an experiment chooses between two settings and records a binary outcome. Many pairs are needed; no dramatic event in a single trial constitutes the test.

The statistic can be understood without following its full derivation. Label each outcome +1 or -1. For any setting pair, average the products of the two outcomes: agreement contributes +1, disagreement -1. Combine the four setting-pair averages by adding three and subtracting the fourth. Under the local causal and independent-setting assumptions, the magnitude cannot exceed 2. Suitable quantum states and settings allow 2 times the square root of 2, about 2.83. The experiment asks whether its measured correlations break the local ceiling of 2, not whether every apparatus reaches the quantum maximum.

The bound is a consistency test. Each local answer sheet must already cover both of its possible settings; it cannot be rewritten after learning the distant choice. Across all four setting combinations, the assignments limit how much the correlations can reinforce one another. Quantum experiments sample those combinations across repeated pairs rather than asking one particle incompatible questions at once. The challenge is to make that sampling trustworthy, with detection, timing and setting choices that do not let the observed sample select only convenient cases.

Freedman and Clauser reported a violation in 1972 using entangled photons. Aspect, Jean Dalibard and Gérard Roger changed analyser settings rapidly in a 1982 experiment and again found the quantum result. Later work improved detector efficiency, separation and random setting choices. In 2015, several teams reported tests closing the major locality and detection loopholes together. No experiment is assumption-free, but the local hidden-instruction model targeted by Bell has lost repeatedly.

The 2022 Nobel Prize in Physics recognised Clauser, Aspect and Anton Zeilinger's experimental work on entanglement, Bell inequalities and quantum information. Their instruments had transformed a dispute about completeness into increasingly demanding constraints. A local model now had to account for all the observed setting combinations, not just invent an explanation for a pair of matching results.

The result sharpened rather than finished the foundations. An underlying theory could retain definite configurations by accepting nonlocal dynamics, as Bohmian mechanics does. Other approaches revise the account of outcomes or change the evolution law.

From thought experiment to controlled object

The post-war period also turned quantum effects into devices. The transistor, demonstrated in 1947, depended on the quantum band structure of semiconductors. The maser and laser used quantised energy levels and stimulated emission. Josephson junctions exposed phase coherence across superconductors. The scanning tunnelling microscope, developed in the early 1980s, used the distance-sensitive tunnelling current between a tip and surface.

Control also made decoherence measurable. In experiments reported in 2003, increasing the background gas pressure reduced fullerene interference as collisions carried information away. In 2004, heating molecules before they entered an interferometer showed a corresponding loss through emitted thermal radiation. Neither manipulation required anyone to inspect the molecules' routes. Researchers changed a physical coupling and measured the resulting change in interference contrast.

Better control made old paradoxes visible one event at a time. Akira Tonomura and colleagues recorded electrons arriving individually behind an electron biprism; the interference pattern accumulated dot by dot. Ion traps, cavities, superconducting circuits and cold atoms allowed researchers to prepare superpositions, entangle systems and watch coherence decay under controlled coupling to an environment.

This control tested a mechanism developed from early work by H. Dieter Zeh in 1970 and extended by Wojciech Zurek and others. Decoherence had become something researchers could vary and measure, rather than invoke whenever an apparatus failed.

Quantum information gave the old concepts an operational vocabulary. Entanglement became a resource to create, verify and consume. No-cloning expressed a limit on copying unknown states. Error correction showed that fragile quantum information can be protected without reading the encoded amplitudes directly. Those developments belong in depth to Quantum Computing, but they fed back into foundations by forcing precise answers to

what can be known, copied and transmitted.

The objects grew larger. Yaakov Fein and colleagues reported interference with organic molecules beyond 25 kilodaltons in 2019. Then came pieces of metal: Sebastian Pedalino and colleagues reported sodium nanoparticles with masses above 170 kilodaltons and more than 7,000 atoms in January 2026. The coherent alternatives concerned their centre-of-mass motion, spread over more than the particles' diameter. This was not a claim that all internal degrees of freedom occupied one pure state.

A pattern of bands was not sufficient proof in the nanoparticle apparatus. Its three light gratings could also give structure to a beam described classically. The researchers therefore varied the middle grating's laser power and compared how the fringe contrast changed with both models. In the demonstrated mass range, the measured dependence followed the quantum prediction rather than the classical one. With still heavier particles in the same apparatus, visible fringes alone did not distinguish the models. The important advance was a discriminating test, not a larger object attached to a familiar photograph.

The theory now

Quantum mechanics is no longer a speculative account of a few spectral lines. Together with relativity in quantum field theory, it underlies particle physics, nuclear physics, chemistry, condensed matter and much of modern technology. Its predictions have survived tests across enormous ranges of energy, distance and precision.

The Standard Model uses quantum fields to describe electromagnetic, weak and strong interactions. General relativity describes gravitation through spacetime geometry. A complete, experimentally established quantum theory of gravity is still missing. That gap is distinct from the measurement problem: one concerns the combination of physical frameworks, the other the relation between the state and experienced outcomes.

Objective-collapse proposals make the latter question experimentally sharper by altering the evolution law. The interference tests described here

found agreement with standard quantum predictions while narrowing the room for specified alternative dynamics. Larger superpositions extend those tests; they do not settle every interpretation at once.

The theory therefore occupies an unusual position. Physicists agree exceptionally well on how to calculate the results of defined experiments and disagree about what the successful calculation says exists. That is not evidence that the subject is arbitrary. It marks the difference between a predictive framework and an ontology.

How we know

Quantum mechanics is supported by converging experiments rather than one decisive demonstration. Spectral lines, the photoelectric effect, Compton scattering, electron and neutron diffraction, Stern-Gerlach splitting, tunnelling rates, atomic clocks, semiconductor behaviour and precision quantum electrodynamics test different parts of the framework.

Single-particle interference confirms that local detections accumulate into phase-sensitive distributions. Bell experiments reject the relevant local hidden-variable inequalities, while controlled decoherence experiments track the loss of accessible interference as environmental information grows.

The historical record needs a different caution. The founders changed their views as experiments and mathematics changed, and their later recollections do not always match the neat positions assigned to them. “Copenhagen” is a family name, not a verbatim manifesto. Agreement on a calculation should not be mistaken for agreement on its meaning.

The evidence supports predictions more directly than ontology. Interference and Bell tests do not select one interpretation from all those sharing their predictions. Larger-object experiments test specified degrees of freedom under controlled conditions, not every possible property of a macroscopic body. Decoherence has been measured by varying environmental interactions. Treating it as collapse would add a conclusion those measurements do not establish.

What People Get Wrong

“Quantum means anything can happen”

Quantum theory assigns probabilities, but it is among the most restrictive theories in science. Within a specified model, an outcome with exactly zero amplitude has zero probability. Conservation laws, symmetries, boundary conditions and selection rules exclude outcomes. Others are allowed only with sharply specified rates.

The myth grows from confusing unpredictable with unconstrained. A single radioactive nucleus does not carry a known decay time in the standard theory, yet a large collection follows a stable statistical law. A detector click may be unpredictable while the interference pattern formed by many clicks is calculable. Randomness lives inside structure.

A fair die is unpredictable and still cannot land on seventeen. Quantum probability is more structured because amplitudes can cancel and symmetries can force exact zeros. Experiments test those numerical patterns across many trials, not merely the existence of surprise.

This matters whenever quantum language is used to excuse a vague claim. A remote event is not made plausible because atoms obey quantum mechanics. Ask for the state, interaction, amplitude and measurement. Without a mechanism, “quantum possibility” is decorative permission for an idea the theory has not supplied.

“An electron is a tiny ball that sometimes becomes a wave”

A detector records an electron at a local place, while an electron state can spread and interfere. Calling one behaviour particle and the other wave preserves two familiar pictures, then encourages the fiction that the electron switches between them.

The quantum object is neither a classical bead nor a classical ripple. Its state supplies amplitudes for possible records and evolves according to

quantum rules. The same arrangement produces local arrivals and a wave-shaped distribution. No moment needs to be chosen when the electron changes costume.

The same warning applies to photons. Interference does not turn light into a continuous classical wave until a detector forces it back into particles. One quantum experiment contains the phase-sensitive evolution and the discrete exchange. The categories are features of classical models, not stages in a hidden timetable.

Try to draw the whole experiment as a travelling bead and the interference defeats you. Draw it as a classical ripple and the local detections defeat you. Neither failure makes the evidence inconsistent. It shows why neither borrowed picture is the theory. A local detection alone cannot establish an unobserved path, and a wavefunction need not be material spread like water.

“Observation means a conscious mind creates reality”

In physics, observation means an interaction capable of producing a record. A path detector can remove interference while its data remain unread. A photographic plate darkens, an atom ionises and an amplifier switches before a person arrives.

Consciousness entered popular accounts because early discussions spoke of observers and a boundary between system and apparatus. Some interpretations give an agent's information a central role, and a few historical proposals linked collapse to awareness. None is required to calculate standard laboratory results, and no experiment shows that human attention makes an otherwise absent detector outcome appear.

Even the phrase “available in principle” concerns physical distinguishability, not a person possessing knowledge. If two path-marking states are orthogonal, interference is lost for the local system whether the file is opened, deleted unread or buried in a laboratory. Recovering interference requires a coherent physical operation, not forgetting.

The distinction matters because mysticism can hide the physical chain. Ask what became correlated with what, which record distinguished the alternatives and whether that information remained reversible. The mind may learn the result. It need not manufacture the interaction that made the result stable.

“The uncertainty principle is caused by clumsy instruments”

Measuring position can disturb momentum, so Heisenberg's microscope remains an appealing picture. It is not the full principle. Position and momentum have non-commuting operators, and a quantum state cannot give both distributions arbitrarily small spreads.

This remains true before anyone touches the system. A wavepacket narrow in position must combine a broad range of wavelengths and momenta. A nearly definite momentum state spreads across position. Better engineering can reduce measurement error; it cannot prepare a state forbidden by the relation.

Spin shows the issue without a microscope. A state can give vertical spin with certainty and horizontal spin with equal probabilities even when both analysers are ideal. Repeating the vertical test confirms the preparation. Changing the axis changes the observable, and no finer dial converts the two incompatible questions into one classical inventory.

The correction separates three issues often merged under one word: uncertainty in the state, error in an instrument and disturbance caused by a measurement. Quantum measurement theory studies all three. Blaming the result on poor eyesight turns a structural limit into a temporary technical fault and misses why incompatible questions require different preparations.

“Entanglement sends messages faster than light”

Entangled particles can produce correlations that violate Bell inequalities across large separations. For a maximally entangled pair such as the singlet, each local spin outcome is equally likely. Changing the detector setting here does not create a controllable pattern in the distant results. The other researcher sees the same local statistics until the two data sets are compared through an ordinary channel.

The myth survives because the correlation appears stronger than a local hidden-instruction model permits. That establishes Bell nonlocality under the theorem's assumptions. It does not supply a signal, reveal a travelling influence or let one side choose the bit received by the other.

Quantum teleportation does not evade the boundary. It transfers an unknown state using shared entanglement, a local joint measurement and classical information sent to the receiver. Until the ordinary message arrives, the receiver cannot reconstruct the state. The protocol uses entanglement precisely while respecting the signalling limit.

This boundary is central. Quantum theory conflicts with the comfortable idea that separated systems carry independent answers to every possible question. It still respects operational no-signalling. Any claim of instant communication must show controllable information transfer, not correlation discovered after conventional messages are exchanged.

“Quantum effects belong only to tiny objects”

Spatial interference becomes harder to display in large objects, but size is not a switch in the equations. The practical issue is coherence. Large systems usually interact through light, heat, vibration, collisions and internal degrees of freedom, so phase information disperses into the environment at extreme speed.

Control those interactions and collective or comparatively massive systems can show interference, tunnelling and sharply quantum states.

Superconductors carry coherent currents. The centre-of-mass interference

of sodium nanoparticles extends the evidence to composite metal clusters. Mechanical resonators can be cooled and controlled near their quantum ground states.

Mass and complexity still impose severe costs. Creating a separated superposition, preventing collisions and thermal radiation, and verifying phase become harder together. A molecule interference result does not imply that a chair can be kept coherently in two rooms. It shows that the boundary is dynamical and quantitative rather than written into the basic law.

The correction changes the mental model. The classical world does not begin at one official diameter. Environmental interaction, the state prepared and the resolution of interest together determine when a classical description succeeds. “Macroscopic” names a demanding experimental regime, not an exemption from quantum law.

“Schrödinger's cat is what quantum mechanics says happens to cats”

Schrödinger invented the cat to expose a difficulty in carrying a microscopic superposition through an apparatus to an ordinary object. It was a criticism of an unresolved boundary, not a cheerful claim that sealed animals routinely occupy a visible half-dead condition.

A real cat interacts with air, light and its own internal activity, even inside a closed box. Decoherence would suppress observable interference between macroscopically distinct records almost instantly. That explains why local tests do not reveal interference between those alternatives. It does not make every foundational question disappear, because interpretations still differ on why one outcome is experienced or whether all decohered outcomes remain in a larger state.

Different interpretations then read the thought experiment differently. Some add collapse, some retain decohered branches, some add definite configurations, and some modify the dynamics. The cat cannot decide among them because it was designed to pose the question. Treating the

illustration as an observed animal state skips the evidence the argument was asking for.

The cat matters as a test of completeness. Any interpretation should explain the chain from microscopic event to stable record without smuggling in an undefined moment when the rules change. The animal is memorable. The boundary problem is the subject.

Use It

Demand the preparation, transformation and measurement

A quantum claim is incomplete if it names only the object. Saying that an electron, atom or molecule is “in superposition” leaves out the basis, the preparation and the later test. The same state can be definite for one observable and spread across alternatives for another.

Reduce any experiment to three operations. How was the state prepared? What interaction or evolution followed? What observable was measured, with which possible records? This sequence separates evidence from mood. A laboratory can prepare a spin along one axis, rotate it, then measure another component. Each verb corresponds to equipment and mathematics.

Use the same discipline when reading a headline. A team may have demonstrated coherence without demonstrating entanglement, entanglement without a Bell violation, or a Bell violation without a useful communication system. A shared adjective does not make these the same achievement.

Separate the state from a single outcome

Quantum mechanics often predicts a distribution rather than the next event. One detector click therefore proves little by itself. The evidence lies in repeated trials, changed settings and the pattern of frequencies that follows.

A one-per-cent outcome is not a scandal for a theory that gave it one per cent. Across enough trials, rare events should occur. Conversely, one lucky match does little for a model vague enough to accommodate almost anything. Compare the whole distribution with the forecast, then ask whether rival explanations forecast something different. The isolated click has no label saying which theory deserves the credit.

This is a useful habit far beyond physics: ask what the model committed itself to before the result arrived. Which records did it allow, with what probabilities, and over how many trials? A vivid event can be memorable while doing little to distinguish explanations. The commitment matters more than the story told afterwards.

Ask whether the alternatives can still interfere

Interference requires more than two possible routes. Their amplitudes must remain coherent and arrive at a common final alternative. A physical record that distinguishes the routes can remove the cross terms even when nobody reads it.

When an experiment claims wave-like behaviour, look for what was varied. Did changing a phase shift the final pattern? Did opening and closing routes alter probabilities in a way ordinary addition cannot explain? Could the apparatus, environment or emitted radiation retain which-path information? These questions identify the mechanism rather than accepting a picture of a wavy object.

They also clarify attempted quantum technologies. Creating a broad superposition is not enough. The device must preserve relative phase, make selected amplitudes interfere and convert the result into a compact record. If the relevant coherence is lost before recombination, the interference-based operation no longer delivers its intended probability pattern. Other useful quantum properties may remain; failure of one operation is not the disappearance of all quantum physics.

Check which trials were counted

A conditional pattern can be strong evidence and still tell a different story from the full record. Quantum erasure makes this unusually clear. Two complementary subsets can each display fringes even though the pooled detections do not. Reporting only one subset without saying how it was selected can make later sorting sound like an alteration of the past.

Ask what the denominator contains. Were all trials included, or only those heralded by an earlier detector? Were detections paired after the event? Was a result retained only after a particular outcome elsewhere? None of these procedures is automatically illegitimate. They define which probability the experiment has measured. The theory and the comparison must describe the same selection.

This distinction also matters in Bell tests. Inefficient detection can leave room for an unrepresentative detected sample, so a persuasive test must address how missing events enter its conclusions. A large correlation among selected clicks does not by itself establish a loophole-free violation. The selection rule belongs beside the result, not beneath it in small print.

Trace where the record went

A measurement result becomes classical-looking when information about an alternative is amplified and copied into many degrees of freedom. The detector changes, the electronics store a bit, photons leave the apparatus, and the environment acquires correlations that are no longer controlled.

Follow that chain. Which component first became correlated with the system? Could the interaction be reversed in principle? At what stage did the distinguishing information spread beyond the experimental degrees of freedom? The answer tells you whether the experiment performed a weak probe, a reversible entangling operation, a destructive measurement or ordinary environmental decoherence.

“Was it observed?” is too blunt a question. A detector can interact without creating a practically irreversible record, and an environment can create a

durable record without a person. Ask instead what could still be recombined. Closing the notebook changes nothing if distinguishing photons have already escaped into the room. The relevant history is in the physical correlations, not the attendance register.

Keep prediction and interpretation on separate lines

Quantum interpretations are serious attempts to say what the formalism describes. They are not interchangeable with the predictions all standard users calculate. Many disagreements concern ontology while leaving ordinary laboratory probabilities unchanged. Some proposals, such as objective-collapse models, can differ empirically and should be judged by experiments.

When hearing a foundational claim, write two sentences. First: what observable result is predicted? Second: what account of reality is offered to explain it? Bell tests constrain the first and eliminate a broad family of local hidden-variable accounts. They do not prove every sentence of many-worlds, Bohmian mechanics or a Copenhagen-style view. Decoherence predicts the suppression of accessible interference. It does not, without further interpretation, settle the status of all outcomes.

Keeping the lines separate permits confidence without pretence. The calculations can be exceptionally secure while the ontology remains contested. Disagreement about meaning does not erase experimental success; experimental success does not grant one preferred meaning without further argument.

The limits

Quantum mechanics is a physical theory, not a universal metaphor. Applying “superposition” to indecision, “observer effect” to social attention or “entanglement” to emotional connection may sound clever and usually removes the mathematical content that made the term useful. Human choices can be uncertain without carrying complex amplitudes. Relationships can be correlated without violating a Bell inequality.

The framework also has scientific boundaries. Non-relativistic quantum mechanics does not cover particle creation, high-energy field processes or gravity in full. Quantum field theory extends the account for relativistic particles and interactions, while a complete tested theory joining quantum principles to gravitation remains absent. Interpretations may be empirically equivalent across current tests, so an experiment confirming standard probabilities cannot choose among them by rhetoric.

Practical applications need their own evidence. Quantum mechanics underlies semiconductors, lasers and magnetic resonance, but attaching quantum to a product does not establish advantage, safety or novelty. The relevant mechanism and comparison must be stated. A true microscopic description can be irrelevant to the claimed macroscopic benefit.

There is still room to ask why nature uses these rules. That question is not answered by promoting a preferred interpretation to measured fact. The explanatory gap is real; a confident voice does not fill it.

The one thing to keep

The useful change is to stop treating the quantum world as a second, exotic world underneath the real one.

The tabletop was quantum matter before anyone placed a delicate interferometer on it. Its atoms have allowed states rather than planetary electron orbits. Their electrons obey exclusion. Their electromagnetic interactions give the material its resistance and its shape. None of this waits for a laboratory to reveal a dramatic superposition. The ordinary object is already a consequence of the unfamiliar rules.

The interferometer asks the same matter to do something less forgiving. It prepares alternatives whose relative phase can affect a later measurement. The detector records one outcome at a time; repetitions expose the distribution. Let another system distinguish the routes and that distribution changes. Stable records and fragile interference are therefore connected features of the same theory, not evidence that nature switches laws at the edge of a microscope.

You can understand that much without settling what ultimately exists. The unresolved question need not spoil the achievement, or become an excuse to believe anything. You now have something firmer than a collection of paradoxes: a way to ask what was prepared, what could still interfere and what the resulting pattern rules out.

The dots on the screen no longer ask you to believe in magic. They ask you to change the calculation. The table holding the screen shows how much of your world already depends on the answer.

Terms

Quantum state

The mathematical object used to predict outcomes for a prepared system. A pure state can be represented by a wavefunction or vector; a density operator also describes mixed states and subsystems entangled with their surroundings.

Wavefunction

A representation of a pure quantum state, often a complex-valued function of position. Its squared magnitude gives position probability density, not probability at an exact point. Probabilities for regions come from adding that density over them.

Amplitude

A complex number attached to an outcome or coherent route in a specified calculation. Amplitudes combine before probability is calculated, allowing reinforcement and cancellation that ordinary positive probabilities cannot produce on their own.

Phase

The angle-like part of a complex amplitude. Overall phase has no observable effect, but relative phase between components changes interference. Preparations with identical immediate outcome probabilities can therefore behave differently when recombined.

Born rule

The rule connecting states to measurement probabilities. For a pure state measured in an orthonormal basis, each coefficient's squared magnitude gives the corresponding outcome probability. Mixed states require the density-operator rule.

Superposition

A coherent linear combination of states in the relevant state space. It retains relative phases that can affect later interference. It is not a collection of simultaneously readable classical values.

Interference

The change in outcome probabilities when amplitudes for indistinguishable alternatives combine. Constructive interference raises a probability; destructive interference lowers it, sometimes to zero. Relative phase determines the result.

Observable

A measurable physical quantity represented by an operator, such as position, momentum, energy or one component of spin. Its eigenvalues are possible ideal measurement outcomes.

Eigenstate

A state producing a particular observable value with certainty in an ideal measurement. A definite vertical spin state can be a superposition for a horizontal test.

Measurement basis

A complete set of mutually orthogonal states used to express the possible answers to a particular ideal measurement. Rotating a spin analyser changes the question asked.

Operator

A mathematical rule acting on quantum states. Operators describe observables and transformations. Their algebra determines how operations combine and which quantities can be jointly sharp.

Hamiltonian

The energy operator, containing kinetic energy, potentials and interactions. In Schrödinger's equation it determines how a state evolves. Its eigenstates identify stationary states in a time-independent system.

Commutator

The difference between applying two operators in opposite orders. A non-zero commutator signals order dependence. For observables, its expectation value enters an uncertainty bound, connecting algebra to measurable spreads.

Uncertainty principle

A lower bound on the joint spreads of particular observables, especially position and momentum. It concerns quantum-state structure, not disturbance caused solely by imperfect instruments. Each spread is defined across repeated identical preparations.

Quantisation

Restriction to selected values or modes under given physical conditions. Bound energies and angular momentum can be discrete, while other quantities or unbound systems retain continuous ranges. There is no universal pellet rule.

Photon

A quantum excitation of the electromagnetic field, carrying energy proportional to frequency and momentum proportional to inverse wavelength. Detections are local even when coherent alternatives contribute.

Orbital

A one-electron state used to describe an atom or molecule. Drawn shapes represent its spatial distribution and phase structure, not a planet-like path. A spatial orbital permits two electron spin states.

Spin

Intrinsic angular momentum with quantised components. Spin is not adequately pictured as a tiny rotating sphere. The measurement axis matters; spin type also determines quantum statistics.

Fermion

A particle described by a many-particle wavefunction antisymmetric under exchange of identical particles. Electrons, protons and neutrons are fermions. Antisymmetry forbids duplicate occupation of one single-particle state.

Boson

A particle described by a many-particle wavefunction symmetric under exchange. Bosons can occupy the same state, enabling collective phenomena such as Bose-Einstein condensation. Photons are bosons; fermion pairs can also behave collectively as bosons.

Pauli exclusion principle

The prohibition on two identical fermions occupying the same single-particle state, including its spin specification. It organises electron shells and contributes to the rising energy required to compress ordinary matter.

Mixed state

A state that cannot be represented by one pure-state vector. It can describe uncertain preparation or the local state of an entangled subsystem. Identical local statistics need not imply the same whole-system state.

Tunnelling

Transmission through a region inaccessible to a classical particle with the same energy. The wavefunction extends beyond the barrier without an energy loan. Barrier width strongly affects transmission.

Entanglement

A joint state that cannot be expressed as a probabilistic mixture of independent states for its parts. For pure states this reduces to non-factorisation. Entanglement contains correlations beyond those created by ordinary shared randomness.

Bell inequality

A numerical constraint on correlations under specified local causal and setting-independence assumptions. Outcome rules, detector settings and missed detections determine which inequality is tested.

Locality

A family of ideas about influences and explanations between separated regions. Bell locality imposes a precise condition on joint outcome probabilities. It is stronger than the prohibition on faster-than-light messages.

Hidden variable

A proposed underlying fact absent from the standard quantum state but intended to determine or explain outcomes. Bell tests constrain local hidden-variable accounts under stated assumptions; they do not exclude every such theory.

Coherence

Phase relationships between specified components of a quantum state that permit interference. An object can lose accessible coherence in one variable while retaining quantum properties in another.

Decoherence

Suppression of a subsystem's accessible interference through entanglement with its environment. It helps explain robust classical-looking alternatives. It does not, by itself, select one outcome or turn the total state into an ordinary statistical mixture.

Quantum field

A quantum description in which particles are excitations of fields. Quantum field theory accommodates particle creation and destruction and combines quantum principles with special relativity. A one-particle picture is then a restricted case.

Go Deeper

The accessible foundations

Philip Ball, *Beyond Weird: Why Everything You Thought You Knew about Quantum Physics Is Different* (University of Chicago Press, 2018). Start here if this book has made the subject interesting rather than settled. Ball explains the formal and experimental core without pretending that every interpretation says the same thing. He is particularly good on information, measurement, decoherence and why “wave-particle duality” can preserve the wrong classical question. The book is argumentative, as any account of foundations must be, but it marks interpretation as interpretation and keeps laboratory evidence in view. Read it for a modern map of the conceptual terrain, then return to the original experiments when one interpretation begins to sound inevitable.

The physical intuition

Richard P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton University Press, 1985). Four public lectures turned into a compact demonstration of amplitude reasoning. Feynman shows how arrows representing amplitudes combine to explain reflection, refraction and interference, with almost no formal machinery. Its scope is electromagnetic interactions rather than all of quantum mechanics, and some historical simplifications should be read as teaching choices. For seeing why amplitudes are calculated first and probabilities second, it remains difficult to beat. Draw the arrows as you read. The method becomes clearer when the geometry is performed rather than admired from the page.

The mathematical bridge

David J. Griffiths and Darrell F. Schroeter, *Introduction to Quantum Mechanics*, third edition (Cambridge University Press, 2018). This is the route from conceptual understanding to working equations. It develops wavefunctions, operators, bound states, angular momentum, spin, identical particles and perturbation theory through problems. Calculus and linear algebra are required, and the book is a course rather than a casual read. Use it when verbal explanations begin to feel slippery and you want to see exactly which claims follow from the formalism. The exercises are part of the argument: calculation exposes assumptions that prose can conceal.

The argument that became an experiment

J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, second edition (Cambridge University Press, 2004). This collection contains Bell's foundational papers, including the 1964 theorem that converted a dispute about completeness and locality into experimental inequalities. Bell writes with unusual clarity, but the essays assume comfort with physics and reward slow reading. Read the original theorem after an accessible account, then compare its precise target with the larger claims often made in its name. It is the best cure for treating “nonlocality” as a slogan. Bell is also an unusually honest guide to the difference between an operational success and an acceptable account of reality.

Notes and Sources

Scope, states and amplitudes

The book distinguishes non-relativistic quantum mechanics from the broader quantum framework, including photons and quantum fields. Its working model connects preparation, evolution and a specified measurement to outcome probabilities. Feynman's *QED* and the Caltech edition of *The Feynman Lectures on Physics*, volume III, supply the amplitude-based explanations; Griffiths and Schroeter and Dirac supply the formal distinctions. A wavefunction represents a pure state. Mixed states require a density operator, and the same local mixed state can arise from different preparations or from entanglement with a larger system. No claim is made that every quantum observable has a discrete spectrum.

Interference and the meaning of a path record

Tonomura and colleagues' 1989 electron experiment used a biprism, not a literal barrier with two slits. Its individual detections built an interference pattern. The slit discussion and the balanced two-output interferometer are explanatory models; the latter assumes lossless components and ideal phase control. Its amplitudes of one half are contributions to specified final outputs, not probabilities assigned to the intermediate paths.

Path distinguishability concerns physical correlations, not human knowledge. Ma and colleagues' quantum-erasure experiment supports the distinction between erasing which-path distinguishability through a suitable quantum operation and deleting an ordinary data file. Conditional subsets can display complementary interference patterns while their unsorted total does not. Neither this result nor delayed selection establishes a signal to the past. The text separates that conditional procedure from coherently reversing a marking interaction.

Confinement, atoms and matter

Allowed bound energies refer to definite-energy states and ideal energy-measurement results, not a prohibition on superpositions. Feynman, Leighton and Sands, volume I, chapter 49, explains how a string's complex motion combines modes; volume III, chapters 8 and 19, supplies the corresponding state and bound-energy distinctions.

The explanation of atomic stability uses the balance between localisation's kinetic-energy cost and Coulomb attraction. It is not a derivation of the stability of bulk matter. Lieb's review explains why the latter additionally requires the many-particle quantum problem and fermionic statistics. Exclusion alone is therefore not offered as a complete explanation of solidity. Orbital diagrams are representations of spatial probability and phase structure, not pictures of electron trajectories.

The identical-particle account follows the exchange symmetry of many-particle wavefunctions. Opposite spins permit two electrons in one spatial orbital because the full single-particle states differ. The spin-statistics connection is stated for the ordinary particles discussed here, without deriving its relativistic field-theoretic basis. Anderson and colleagues' 1995 dilute-gas experiment supplies the rubidium-condensate example. Earlier superfluid phenomena are not erased by calling that experiment a milestone in controlled atomic gases.

Spin, measurement and uncertainty

Gerlach and Stern's 1922 experiment separated a silver-atom beam in a non-uniform magnetic field. Electron spin had not yet been proposed. The modern interpretation must not be attributed to their original experimenters. The sequence of differently oriented spin analysers is explicitly idealised, rather than a report of what their apparatus did.

The discussion distinguishes state-preparation uncertainty, instrumental error and measurement disturbance. Heisenberg's 1927 microscope argument helped introduce the issue, but position-momentum uncertainty also follows from the state formalism independently of an inaccurate instrument. Statements about certainty on immediate repetition assume an ideal repeatable measurement and no intervening evolution that changes the measured quantity. Not every measurement absorbs or destroys the system.

Tunnelling and fusion

The barrier explanation concerns a time-independent potential. Transmission does not require temporary violation of energy conservation. The simple exponential dependence applies to the opaque-barrier approximation used in the example, not every possible barrier shape or resonance. Gamow and, independently, Gurney and Condon applied wave mechanics to alpha decay in 1928.

Solar fusion requires more than barrier penetration. The thermal distribution includes a high-energy tail, but classical over-barrier encounters are far too rare to account for the observed process. Quantum penetration increases access to nuclear distances; reaction probabilities then depend on the nuclear interaction. In the proton-proton chain, formation of deuterium also requires a weak-interaction conversion. Nguyen and Vanasse's proton-proton fusion calculation supports that distinction. No numerical stellar reaction rate is inferred here from a one-dimensional barrier model.

Binnig, Rohrer, Gerber and Weibel's 1982 work supports the scanning tunnelling microscope account. The measured current depends strongly on

separation and on electronic structure. An atomic-resolution image is a reconstructed measurement of that interaction, not an optical photograph of rigid spheres.

The early experiments and the new formalism

Planck's radiation formula was presented in October 1900; his statistical derivation followed in December, with the fuller paper published in 1901. His 1920 Nobel lecture describes the experimental pressure from long-wavelength departures from Wien's law. The later ultraviolet-catastrophe diagnosis must not be projected backwards as the event that prompted the December proposal.

Einstein's 1905 paper supplies the light-quantum proposal and the photoelectric energy relation. The body specifies the ordinary single-photon regime: it does not deny multiphoton emission under sufficiently intense illumination. Millikan's 1916 measurements supported the relation while his discussion remained resistant to Einstein's general light-quantum picture. Compton's 1923 scattering paper supplies a separate energy-and-momentum test.

Franck and Hertz's mercury experiments of 1914 established characteristic energy exchange; their interpretation was not instantly identical to the later textbook account. Franck's Nobel lecture recounts that development. The experiment is not described as proof of every feature of Bohr's orbital model.

Bohr, Heisenberg, Born and Schrödinger's original papers anchor the sequence from permitted orbits to matrix and wave mechanics. Pais and Jammer provide the wider chronology and distribution of credit. The time-evolution account follows the standard Schrödinger framework: a time-independent Hamiltonian has stationary energy states, while relative phases between different energy components evolve. The Solvay debates are summarised without invented conversation or an allegedly verbatim Einstein-Bohr exchange.

Entanglement and Bell's assumptions

Einstein, Podolsky and Rosen's 1935 paper argued for incompleteness under a criterion of reality and a locality condition. Schrödinger's response introduced the cat as a thought experiment and examined entanglement. The book does not report a performed cat experiment.

Bell's 1964 result and the 1969 Clauser-Horne-Shimony-Holt formulation concern specified local causal models and setting-independence assumptions. Brunner and colleagues explain the modern distinction between entanglement, Bell nonlocality and no-signalling. In the CHSH illustration, each correlation is an average of products of outcomes labelled plus or minus one. The local bound of 2 and quantum maximum of $2\sqrt{2}$ are bounds on a dimensionless combination of four correlations. They are not percentages, detector efficiencies or measured values attributed to every Bell experiment.

Freedman and Clauser's 1972 experiment, Aspect, Dalibard and Roger's 1982 time-varying analysers, and the 2015 Hensen, Giustina and Shalm experiments establish the experimental progression. Closing major detection and locality loopholes does not remove every assumption about the source, settings or statistical analysis. Bell tests do not refute all hidden-variable theories; explicitly nonlocal accounts remain outside their local target.

Unbiased individual spin outcomes refer to the singlet example. The general no-signalling statement is that a distant local choice cannot controllably change the other party's unconditional outcome distribution. Conditional correlations can change without enabling a remote message.

Environmental interaction and classical appearance

Zeh, Zurek and Schlosshauer support the account of environmental entanglement, reduced-state interference and robust pointer states. Schlosshauer's review is in volume 76, labelled 2004, but was published online on 23 February 2005; the bibliography records both rather than treating them as two works.

Hornberger and colleagues varied gas pressure in a 2003 matter-wave experiment. Hackermüller and colleagues studied decoherence through thermal radiation in 2004. These controlled interventions support the physical mechanism rather than a claim that all loss of visibility has one cause. Ordinary trajectories additionally require suitable states, forces and resolution. Decoherence alone is not a universal derivation of Newtonian motion, and it does not select one unique outcome from a globally unitary state.

The Copenhagen family, Everettian accounts, Bohmian mechanics and objective-collapse proposals are distinguished rather than given equal evidential status as separate established discoveries. Objective-collapse models modify dynamics and can face experimental bounds. An interpretation that reproduces the same predictions is a different kind of claim from a tested modification.

Larger objects, publication dates and experimental scope

Fein and colleagues' 2019 study reported quantum superposition of molecules beyond 25 kilodaltons. The nanoparticle result used here is Pedalino and colleagues' final *Nature* paper, published on 21 January 2026, not merely its 2025 preprint. Its selected sodium-cluster distribution was centred near 172 kilodaltons, corresponding to roughly 7,500 atoms. The body uses the paper's rounded description of more than 170 kilodaltons and more than 7,000 atoms.

The tested variable was centre-of-mass motion. This does not imply that every internal degree of freedom was pure or that an arbitrary warm object would display the same interference. The paper's laser-power comparison was important because fringes alone did not discriminate quantum interference from a classical shadow effect. Its heavier-cluster measurements illustrate that limitation. Publication in 2026 is not asserted to be the date on which all measurements were taken.

Information, applications and provenance

Wootters and Zurek support the impossibility of perfectly cloning an arbitrary unknown state. Bennett and colleagues' 1993 protocol supports teleportation using shared entanglement and classical communication. Shor's 1995 work supports quantum error correction without ordinary readable backup copies. These results illustrate physical constraints; algorithms, hardware rankings and commercial forecasts belong to *Quantum Computing in a Hurry*.

The book's gloves, string, die, ball and dust-grain examples are illustrations. Balanced interferometers and repeated ideal spin measurements are stated as models, not unreported laboratory events. Named historical experiments are documented by the works above. No composite scene, imagined dialogue or private motive is presented as fact.

Central explanations, important historical claims and retained current material were checked for this edition on 5 September 2026. The contemporary experiment supports quantum predictions in its stated regime and bounds specified alternatives. It is not made to certify every domain of quantum physics, settle interpretation or supply a theory of quantum gravity.

Bibliography

Primary and original sources

Anderson, M. H., J. R. Ensher, M. R. Matthews, C. E. Wieman and E. A. Cornell. "Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor." *Science* 269 (1995): 198-201. DOI: 10.1126/science.269.5221.198.

Aspect, Alain, Jean Dalibard and Gérard Roger. "Experimental Test of Bell's Inequalities Using Time-Varying Analyzers." *Physical Review Letters* 49 (1982): 1804-1807. DOI: 10.1103/PhysRevLett.49.1804.

Bell, J. S. "On the Einstein Podolsky Rosen Paradox." *Physics Physique Fizika* 1 (1964): 195-200. DOI: 10.1103/PhysicsPhysiqueFizika.1.195.

Bennett, Charles H., Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres and William K. Wootters. "Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels." *Physical Review Letters* 70 (1993): 1895-1899. DOI: 10.1103/PhysRevLett.70.1895.

Binnig, Gerd, Heinrich Rohrer, C. Gerber and E. Weibel. "Surface Studies by Scanning Tunneling Microscopy." *Physical Review Letters* 49 (1982): 57-61. DOI: 10.1103/PhysRevLett.49.57.

Bohr, Niels. "On the Constitution of Atoms and Molecules, Part I." *Philosophical Magazine* 26 (1913): 1-25. DOI: 10.1080/14786441308634955.

Born, Max. "Zur Quantenmechanik der Stoßvorgänge." *Zeitschrift für Physik* 37 (1926): 863-867. DOI: 10.1007/BF01397477.

Clauser, John F., Michael A. Horne, Abner Shimony and Richard A. Holt. "Proposed Experiment to Test Local Hidden-Variable Theories." *Physical Review Letters* 23 (1969): 880-884. DOI: 10.1103/PhysRevLett.23.880.

Compton, Arthur H. "A Quantum Theory of the Scattering of X-rays by Light Elements." *Physical Review* 21 (1923): 483-502. DOI: 10.1103/PhysRev.21.483.

Davisson, Clinton and Lester H. Germer. "Diffraction of Electrons by a Crystal of Nickel." *Physical Review* 30 (1927): 705-740. DOI: 10.1103/PhysRev.30.705.

Einstein, Albert, Boris Podolsky and Nathan Rosen. "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* 47 (1935): 777-780. DOI: 10.1103/PhysRev.47.777.

Einstein, Albert. "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt." *Annalen der Physik*, fourth series, 17 (1905): 132-148. DOI: 10.1002/andp.19053220607.

Fein, Yaakov Y., Philipp Geyer, Patrick Zwick, Filip Kialka, Sebastian Pedalino, Marcel Mayor, Stefan Gerlich and Markus Arndt. "Quantum Superposition of Molecules beyond 25 kDa." *Nature Physics* 15 (2019): 1242-1245. DOI: 10.1038/s41567-019-0663-9.

Franck, James. "Transformation of Kinetic Energy of Free Electrons into Excitation Energy of Atoms by Impacts." Nobel lecture, 11 December 1926. Nobel Foundation digital edition.

Freedman, Stuart J. and John F. Clauser. "Experimental Test of Local Hidden-Variable Theories." *Physical Review Letters* 28 (1972): 938-941. DOI: 10.1103/PhysRevLett.28.938.

Gamow, George. "Zur Quantentheorie des Atomkernes." *Zeitschrift für Physik* 51 (1928): 204-212. DOI: 10.1007/BF01343196.

Gerlach, Walther and Otto Stern. "Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld." *Zeitschrift für Physik* 9 (1922): 349-352. DOI: 10.1007/BF01326983.

Giustina, Marissa, et al. "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons." *Physical Review Letters* 115 (2015): 250401. DOI: 10.1103/PhysRevLett.115.250401.

Gurney, Ronald W. and Edward U. Condon. "Wave Mechanics and

Radioactive Disintegration." *Nature* 122 (1928): 439. DOI: 10.1038/122439a0.

Hackermüller, Lucia, Klaus Hornberger, Björn Brezger, Anton Zeilinger and Markus Arndt. "Decoherence of Matter Waves by Thermal Emission of Radiation." *Nature* 427 (2004): 711-714. DOI: 10.1038/nature02276.

Heisenberg, Werner. "Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik." *Zeitschrift für Physik* 43 (1927): 172-198. DOI: 10.1007/BF01397280.

Heisenberg, Werner. "Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen." *Zeitschrift für Physik* 33 (1925): 879-893. DOI: 10.1007/BF01328377.

Hensen, Bas, et al. "Loophole-Free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres." *Nature* 526 (2015): 682-686. DOI: 10.1038/nature15759.

Hornberger, Klaus, Stefan Uttenthaler, Björn Brezger, Lucia Hackermüller, Markus Arndt and Anton Zeilinger. "Collisional Decoherence Observed in Matter Wave Interferometry." *Physical Review Letters* 90 (2003): 160401. DOI: 10.1103/PhysRevLett.90.160401.

Ma, Xiao-song, et al. "Quantum Erasure with Causally Disconnected Choice." *Proceedings of the National Academy of Sciences* 110 (2013): 1221-1226. DOI: 10.1073/pnas.1213201110.

Millikan, Robert A. "A Direct Photoelectric Determination of Planck's 'h'." *Physical Review* 7 (1916): 355-388. DOI: 10.1103/PhysRev.7.355.

Nguyen, Ha S. and Jared Vanasse. "Tritium β Decay and Proton-Proton Fusion in Pionless Effective Field Theory." *Physical Review C* 110 (2024): L021001. DOI: 10.1103/PhysRevC.110.L021001.

Pedalino, Sebastian, et al. "Probing Quantum Mechanics with Nanoparticle Matter-Wave Interferometry." *Nature* 649 (2026): 866-870. DOI: 10.1038/s41586-025-09917-9.

Planck, Max. Nobel lecture, 2 June 1920. Nobel Foundation digital edition.

Planck, Max. "Ueber das Gesetz der Energieverteilung im Normalspectrum." *Annalen der Physik*, fourth series, 4 (1901): 553-563. DOI: 10.1002/andp.19013090310.

Schrödinger, Erwin. "Die gegenwärtige Situation in der Quantenmechanik." *Naturwissenschaften* 23 (1935): 807-812, 823-828, 844-849.

Schrödinger, Erwin. "Quantisierung als Eigenwertproblem." Erste Mitteilung. *Annalen der Physik*, fourth series, 79 (1926): 361-376. DOI: 10.1002/andp.19263840404.

Shalm, Lynden K., et al. "Strong Loophole-Free Test of Local Realism." *Physical Review Letters* 115 (2015): 250402. DOI: 10.1103/PhysRevLett.115.250402.

Shor, Peter W. "Scheme for Reducing Decoherence in Quantum Computer Memory." *Physical Review A* 52 (1995): R2493-R2496. DOI: 10.1103/PhysRevA.52.R2493.

Thomson, G. P. and A. Reid. "Diffraction of Cathode Rays by a Thin Film." *Nature* 119 (1927): 890. DOI: 10.1038/119890a0.

Tonomura, Akira, Jiro Endo, Tsuyoshi Matsuda, Takeshi Kawasaki and Hiroji Ezawa. "Demonstration of Single-Electron Buildup of an Interference Pattern." *American Journal of Physics* 57 (1989): 117-120. DOI: 10.1119/1.16104.

Wootters, William K. and Wojciech H. Zurek. "A Single Quantum Cannot Be Cloned." *Nature* 299 (1982): 802-803. DOI: 10.1038/299802a0.

Zeh, H. Dieter. "On the Interpretation of Measurement in Quantum Theory." *Foundations of Physics* 1 (1970): 69-76. DOI: 10.1007/BF00708656.

Modern works and technical syntheses

Ball, Philip. *Beyond Weird: Why Everything You Thought You Knew about Quantum Physics Is Different*. Chicago: University of Chicago Press, 2018.

Bell, J. S. *Speakable and Unspeakable in Quantum Mechanics*. 2nd ed. Cambridge: Cambridge University Press, 2004.

Brunner, Nicolas, Daniel Cavalcanti, Stefano Pironio, Valerio Scarani and Stephanie Wehner. "Bell Nonlocality." *Reviews of Modern Physics* 86 (2014): 419-478. DOI: 10.1103/RevModPhys.86.419.

Dirac, P. A. M. *The Principles of Quantum Mechanics*. 4th ed. Oxford: Clarendon Press, 1958.

Feynman, Richard P. *QED: The Strange Theory of Light and Matter*. Princeton: Princeton University Press, 1985.

Feynman, Richard P., Robert B. Leighton and Matthew Sands. *The Feynman Lectures on Physics*. Volumes I and III. Caltech online edition, accessed 5 September 2026.

Griffiths, David J. and Darrell F. Schroeter. *Introduction to Quantum Mechanics*. 3rd ed. Cambridge: Cambridge University Press, 2018.

Jammer, Max. *The Conceptual Development of Quantum Mechanics*. 2nd ed. Los Angeles: Tomash Publishers; Woodbury, NY: American Institute of Physics, 1989.

Lieb, Elliott H. "The Stability of Matter." *Reviews of Modern Physics* 48 (1976): 553-569. DOI: 10.1103/RevModPhys.48.553.

Pais, Abraham. *Inward Bound: Of Matter and Forces in the Physical World*. Oxford: Clarendon Press, 1986.

Royal Swedish Academy of Sciences. *Scientific Background on the Nobel Prize in Physics 2022*. Stockholm: Royal Swedish Academy of Sciences, 2022.

Schlosshauer, Maximilian. "Decoherence, the Measurement Problem, and Interpretations of Quantum Mechanics." *Reviews of Modern Physics* 76 (2004): 1267-1305. Published 23 February 2005. DOI: 10.1103/RevModPhys.76.1267.

Zurek, Wojciech H. "Decoherence, Einselection, and the Quantum Origins of the Classical." *Reviews of Modern Physics* 75 (2003): 715-775. DOI: 10.1103/RevModPhys.75.715.