Outline of Quantum Mechanical Waves
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Contents

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PHYS>Physics>Quantum Mechanics>Waves

matter wave

In classical physical space, particles have definite positions and momenta, not probabilities of positions and momenta. If physical space has no external forces, positions and momenta are independent. If physical space has force fields, position change changes momentum in only one way, according to energy conservation. Because particles have definite positions and momenta, and classical configuration space has only real numbers, classical configuration space has no real-number/imaginary-number interactions and so no waves. The Hamiltonian function represents energy as a function of momentum (kinetic energy) and space (potential energy) coordinates.

In quantum-mechanical physical space, particles have probabilities of positions and momenta. Quantum-mechanical physical space has energy conservation, but positions and momenta are not independent, so energy-conservation equation (Schrödinger equation) and S-matrix theory, which relate kinetic-energy change and momentum to potential-energy change and position, have complex numbers. Exponentials with complex-number exponents represent cosine and sine waves. (Maxwell's equations relate kinetic-energy change and momentum to potential-energy change and position, and solutions are electromagnetic waves.) Frequency is time derivative. Wave number is spatial derivative. The time derivative introduces an imaginary number to multiply the time derivative to give a real number.

Quantum-mechanical configuration space (phase space) has complex-number particle position and momentum coordinates. Along each configuration-space dimension, real and imaginary numbers interact to make helical scalar waves {matter wave}| {de Broglie wave} {probability wave}.

scalar

Electromagnetic waves are vector waves, because electric and magnetic forces and fields have direction, electromagnetic waves propagate in a direction, and energy travels in that direction. Matter waves are scalar, because they are not about forces or fields, have no energy, and do not propagate and so do not travel and are standing waves. Scalar waves have amplitude but no direction.

phase space

Matter waves are not in physical space.

wavelength

Wavelength determines possible particle positions and momenta, at maximum-displacement positions. Frequency and phase affect amplitude.

amplitude and probability

Amplitude determines probability that particle is at that position or momentum.

frequency and kinetic energy

Particle kinetic energy E determines matter-wave frequency f: $E = h * f$, where h is Planck constant. For higher energies, matter waves have higher frequencies and lower wavelengths. Particle momentum p determines matter-wave wavelength w: $h = p * w$. Theoretical matter-wave velocity v increases with particle kinetic energy: $v = f * w = (E/h) * (h/p) = E/p$.

transverse wave

Real and imaginary number interactions make transverse waves around each phase-space dimension.

length

Matter waves are in configuration space, which has infinitely-long dimensions, so matter waves are infinitely long. By uncertainty principle, matter waves extend through all space, but with low amplitude outside physical system.

no propagation and no energy

Because they are infinitely long, matter waves do not propagate, are standing waves, and have no travel, no velocity, no energy, and no leading or trailing edge. Matter waves resonate in phase space.

positions, points, and intervals

Waves require one wavelength to be a wave, so there is no definite position. For waves, positions cannot be points but are one-wavelength or half-wavelength intervals.

solidity

Matter waves have width of at least one wavelength, so they cause matter to spread over space, not be at points. Matter waves make matter have area, and matter appears solid.

momentum and position

In quantum mechanics, unlike classical mechanics, momentum and position are not independent, because amplitude relates to position, frequency relates to momentum, wave amplitude-change rate relates to wave frequency-change rate, wavelength relates to position uncertainty, and amplitude-change rate relates to momentum uncertainty.

particle sizes

Large objects have high matter-wave frequencies. At high frequencies, matter-wave properties are undetectable, because wavelengths are too small, so classical mechanics applies. Small objects have low matter-wave frequencies, so atomic particles have detectable quantum properties.

waves and quanta

Resonating waves have fundamental frequency and harmonic overtones. Particles have matter waves with harmonic frequencies. Harmonic frequencies correspond to a series of positions or energy/momentum levels, separated by equal amounts (quantum).

Waves change frequency without passing through intermediate frequencies. No intermediate frequencies means no intermediate positions or energies/momenta. Matter waves explain why particles have discrete energy levels, separated by quanta, and why, during energy-level transitions, particles never have in-between energy levels. Particles also have discrete locations, separated by quantum distances.

physical systems

In free space, particle matter waves have a small range of frequencies and superpose to make a wave packet. Particle systems superpose particle matter waves to make system matter waves. Non-interacting particles have dependent matter waves that add non-linearly (entangle). In atoms and molecules, electrons, neutrons, and protons have phase-space matter waves that represent transitions among atomic orbits.

Electrons cannot be near nucleus, because then electron matter-wave interacts with proton matter-wave, and atom collapses.

philosophy

Perhaps, matter waves are particles, only associate with particles, are mathematical descriptions, or are all that observers can know.

de Broglie relation

Matter-wave wavelength equals Planck constant divided by momentum {de Broglie relation}|.

tunneling

In quantum mechanics, matter-wave amplitude determines probability that particle is at that position. Matter waves are infinite and so have positive amplitude at all space points. Therefore, unlike classical mechanics, particles have a probability of being outside potential-energy barriers {tunneling}|.

At barriers, particle waves reflect back or refract through. Particles with higher matter-wave frequency and more energy have more refraction. As difference between barrier potential energy and particle energy increases, reflection {anti-tunneling} increases.

wave packet

Matter waves are infinitely long. Because particle matter waves have fundamental frequency and its harmonics, particles have an infinite number of different-frequency matter waves. Because particles interact with other universe masses and charges, particles have matter waves differing in wavelength by infinitesimally small amounts. Superposition of an infinite number of infinitely long waves, differing in wavelength by infinitesimally small amounts, makes significant amplitude {wave packet}| in one region and insignificant amplitudes in all other regions. Particles are matter-wave packets.

time

Over time, as superposition makes different results, wave packets can disappear and reappear. Wave superposition can narrow or broaden wave-packet duration. and broadening frequency range.

size

Wave packets have three to ten oscillations, with maximum amplitude in center and no amplitude at edges. Longest wavelengths are in middle and smallest wavelengths are at edges. If wavelength range is small, packet is wide. If wavelength range is large, packet is narrow.

speed

Wave packets travel at particle speed, but wave-packet component waves travel at slower and faster speeds.

frequencies

Matter-wave-packet frequency varies directly with particle energy. Wave superposition can narrow or broaden wave-packet frequency range. If wave packet has many frequencies, volume is small, but energy is big. If wave packet has few frequencies, volume is large, and energy is small.

dispersion

Due to dispersion, wave packets spread out lengthwise and transversely.

PHYS>Physics>Quantum Mechanics>Waves>Entanglement

entanglement

In classical mechanics, positions and momenta (and energies and times) are independent variables, but in quantum mechanics, they are dependent variables and interact in wavefunctions. In classical mechanics, when two or more particles interact, system properties sum particle properties. In quantum mechanics, when two or more particles interact, system properties multiply and sum particle properties, and particle wavefunctions combine constructively and/or destructively to make a system wavefunction {entanglement}|. If two (indistinguishable) particles entangle, they both travel together on all possible state paths available to them, and they interfere with each other's independent-particle wavefunctions along each path. For example, two particles created simultaneously form one system with one wavefunction.

Entanglement does not put particles into unchanging states (that observers measure later). Neither do particle states continually change state as they move through space-time (not like independent neutrinos, which change properties as they travel). Therefore, observation method, time, and space position and orientation do not determine observed particle state. In quantum mechanics, particles have probabilities, depending on particles and system, of taking all possible space-time and particle-interaction paths, and measurement finds that the particle has randomly gone into one of the possible particle states.

system wavefunction

When two particle wavefunctions add, system-wavefunction frequency is the beat frequency of the two particle-wavefunction frequencies, and is lower than those frequencies. System wave packet has smaller spatial extension than particle wave packets, and has higher amplitude (more energy) at beat-frequency wavelengths. Quantum-mechanical particle and system wavefunctions have non-zero fundamental frequency and its harmonic frequencies and have non-zero amplitudes over all space and time. Systems spread out over space and time.

system wavefunction decoherence

After entanglement, system wavefunction lasts until outside disturbances, such as measurement, particle collision or absorption, and electromagnetic, gravitational, or nuclear force field, interact with one or more particles. At that definite time and position, system wavefunction separates into independent particle wavefunctions (decoherence). Whole system wavefunction ends simultaneously over whole extent.

measurement

By uncertainty principle, experimenters can precisely measure either particle energy or particle time (or momentum or position) but not both. After two entangled particles separate, separate instruments can measure each particle's energy (or momentum) precisely and simultaneously and then communicate to determine the exact difference.

measurement: speculation

Perhaps, unobserved particles and systems are two-dimensional (but still in three-dimensional space). Observation then puts particles and systems into three dimensions. People observe only three-dimensional space. For example, observers see that gloves are right-handed or left-handed. Perhaps, unobserved quantum-mechanical-size gloves actually have no thickness and so have only two dimensions, so unobserved right-handed and left-handed gloves are the same, because they can rotate in three-dimensional space to superimpose and be congruent. Perhaps, unobserved clockwise and counter-clockwise particle spins are two-dimensional and so are equivalent. (Note that a two-dimensional glove appears right-handed or left-handed depending on whether the observation point is above or below the glove.)

Perhaps, unobserved particles and systems randomly, continually, and instantaneously turn inside out (and outside in), in three-dimensional space. Observation stops the process. For example, turning a right-handed glove inside out makes a left-handed glove, and vice versa. Perhaps, unobserved quantum-mechanical-size gloves continually and instantaneously turn inside out in three-dimensional space and so are equally right-handed and left-handed. Perhaps, unobserved clockwise and counter-clockwise particle spins continually interchange. (Note that a glove appears right-handed or left-handed depending on when the process stops.)

Perhaps, unobserved quantum-mechanical-size particle and system states are indeterminate and follow quantum-mechanical rules because space-time is not conventional four-dimensional space-time. Observation requires conventional three-dimensional space, and randomly makes definite three-dimensional particle and system states, with probabilities. Perhaps, time is not real-number time, but complex-number or hypercomplex-number time. Real-number times are separate, but imaginary-number times are not. Perhaps, space is not real-number space, but complex-number or hypercomplex-number space. Real-number distances are separate, but imaginary-number distances are not.

Observations measure real-number part of complex-number variables. Perhaps, wavefunction imaginary-number part continues after observation.

Perhaps, Necker cubes illustrate the effects of observation. Observer angle to Necker cube determines whether observer sees right-facing or left-facing Necker cube. Effects may be linear with angle or depend on cosine of angle.

interacting electrons and spin

If a process creates two electrons, momentum sum is the same before and after creation, by momentum conservation, and electrons move away from each other at same velocity along a straight line. Angular-momentum sum is the same before and after creation, by angular-momentum conservation. (If two separate electrons entangle, momentum sum and angular-momentum sum are the same before and after interaction.)

By quantum mechanics, measured spin is always +1/2 or -1/2. Because the electrons are in a system, one cannot know which has +1/2 spin and which -1/2 spin. Both electrons share a system wavefunction that superposes the state (wavefunction) in which first electron has spin +1/2 unit and second has spin -1/2 unit and the state (wavefunction) in which first electron has spin -1/2 unit and second has spin +1/2 unit, with zero total angular momentum in any direction. Two wavefunctions can superpose constructively (add) or destructively (subtract). Because two electrons are distinguishable, the two wavefunctions add, so system wavefunction is anti-commutative.

One possibility is that one particle has positive 1/2 unit spin along z-axis (motion line), and other particle has negative 1/2 unit spin along z-axis. See Figure 1.

After two particles interact and move apart, separate spin detectors can measure around any axis for first particle and around any axis for second particle, simultaneously or in succession. For example, the axes can be z-axis (motion line), x-axis, and y-axis. See Figure 2. Measuring spin around an axis fixes one electron's spin at +1/2 (or -1/2) and fixes the other electron's spin around an axis at -1/2 (or +1/2), to conserve angular momentum.

spin: possible axis and spin combinations

By quantum mechanics, left electron has spin +1/2 half the time and spin -1/2 half the time, around any axis, say z-axis. Around same z-axis, right electron always has opposite spin: left=z+ right=z- or left=z- right=z+. Around x-axis, right electron has opposite spin (while y-axis has same spin), same spin (while y-axis has opposite spin), opposite spin (while y-axis has opposite spin), or same spin (while y-axis has same spin): x-y+z-, x+y-z-, x-y-z-, x+y+z-; x-y+z+, x+y-z+, x-y-z+, x+y+z+. For right-electron z-axis compared to left-electron z-axis, spins are opposite all of the time: z+z-, z+z-, z+z-. z+z-. For right-electron x-axis or y-axis compared to left-electron z-axis, spins are same 1/2 of time and opposite 1/2 of time: z+x-, z+y+; z+x+, z+y-; z+x-, z+y-; z+x+, z+y+. See Figure 3. Because quantum mechanics has random probabilities, left and right electrons have same spin half the time and opposite spin half the time.

However, quantum mechanics with non-randomness (due to local real hidden factors) makes a different prediction. Non-random hidden factors correlate right and left spins, to conserve angular momentum. If left=x+y+z+, right=x-y-z-. If left=x-y+z+, right=x+y-z-. If left=x+y-z+, right=x-y+z-. If left=x-y-z+, right=x+y+z-. If left=x-y-z-, right=x+y+z+. If left=x+y-z-, right=x-y+z+. If left=x-y+z-, right=x+y-z+. If left=x+y+z-, right=x-y-z+. See Figure 4. For right-electron z-axis compared to left-electron z-axis, spins are opposite all the time. For right-electron x-axis or y-axis compared to left-electron z-axis, spins are same 4/9 of time and opposite 5/9 of time, higher than the 1/2 level for quantum mechanics. Local hidden variable theories correlate events through hidden variable(s), making probabilities non-random. Quantum mechanics has no more-fundamental factors and introduces uncertainties, and so is random. Therefore, correlated outcomes in classical theories have different probabilities than in quantum mechanics. Experiments show that outcomes are random, so there are no local hidden factors and/or no real hidden factors.

if infinite light speed

Perhaps, entanglement over large distances and times has no non-locality problems if light speed is infinite, as in Newton's gravitational theory. Assume that relativity is true but with light speed infinite. Time is zero for light, and speed is always infinite for all observers, so all objects are always in contact. However, light speed is finite.

action at distance

Wavefunctions do not represent physical forces or energy exchanges, so space and time do not matter. If system wavefunction does not decohere, system particles and fields remain connected, even over long duration and far distances. Experiments that measure energy and time differences, or momentum and position differences, show that particles remained entangled over far distances and long times, and that wavefunction collapse immediately affects all system particles and fields, no matter how distant (action at a distance). Seemingly, new information about one particle travels instantly to second particle. See Particle Interference, Scientific American 269(August): 52-60 [1993].

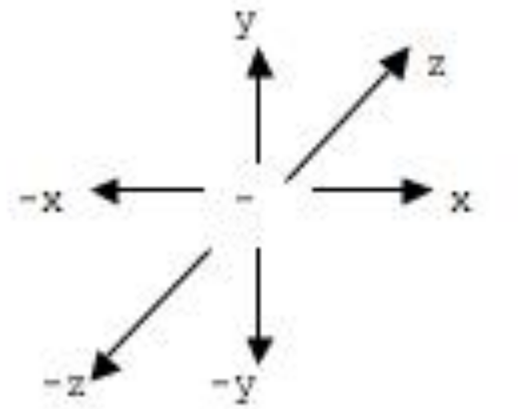
However, information about collapse only travels at light speed, preserving special relativity theory that physical effects faster than light speed are not possible. Observers must wait for light to travel to them before they become aware of information changes. All physical laws require local interaction through field-carrying particle exchanges, which result in space curvatures. All physical communication happens when particles are in contact and interact, so there is no actual action at a distance.

teleportation

After particle entanglement, particle wavefunctions have specific relations. By manipulating particle properties at interaction and at wavefunction collapse, experimenters can transfer particle properties from one particle to another particle, even far away, though the particles have no physical connection at collapse time.

Figure 1

Figure 2



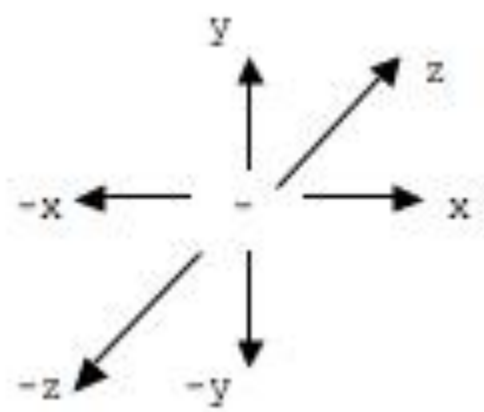


Figure 3

Quantum mechanics goes into states randomly and so does not correlate left-electron and right-electron spins.

If left electron is z+, right electron is:

x- or y+ or z- 25% of time
x+ or y- or z- 25% of time
x- or y- or z- 25% of time
x+ or y+ or z- 25% of time

For right-electron z-axis compared to left-electron z-axis, spins are opposite all of the time:
z+z-
z+z-
z+z-
z+z-

For right-electron x-axis or y-axis compared to left-electron z-axis, spins are same 1/2 of time and opposite 1/2 of time:
z+x-, z+y+
z+x+, z+y-
z+x-, z+y-
z+x+, z+y+

If left electron is z-, right electron is:

x- or y+ or z+ 25% of time
x+ or y- or z+ 25% of time
x- or y- or z+ 25% of time
x+ or y+ or z+ 25% of time

By symmetry with the above:
For right-electron z-axis compared to left-electron z-axis, spins are opposite all of the time.
For right-electron x-axis or y-axis compared to left-electron z-axis, spins are same 1/2 of time and opposite 1/2 of time.

Figure 4

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Non-random quantum mechanics correlates left and right electron results:

If left electron is z+:
If left=x+y+z+, right=x-y-z- 25% of time.
If left=x-y+z+, right=x+y-z- 25% of time.
If left=x+y-z+, right=x-y+z- 25% of time.
If left=x-y-z+, right=x+y+z- 25% of time.

left=x+y+z+, right=x-y-z- has the pairs:
x+x-, x+y-, x+z-, y+x-, y+y-, y+z-, z+x-, z+y-, z+z-
so spins are same 0 times and opposite 9 times.
.
left=x-y+z+, right=x+y-z- has the pairs:
x-x+, x-y-, x-z-, y+x+, y+y-, y+z-, z+x+, z+y-, z+z-
so spins are same 4 times and opposite 5 times.

left=x+y-z+, right=x-y+z- 25% of time.
x+x-, x+y+, x+z-, y-x-, y-y+, y-z-, z+x-, z+y+, z+z-
so spins are same 4 times and opposite 5 times.

left=x-y-z+, right=x+y+z- 25% of time.
x-x+, x-y+, x-z-, y-x+, y-y+, y-z-, z+x+, z+y+, z+z-
so spins are same 4 times and opposite 5 times.


If left electron is z+:
If left=x-y-z-, right=x+y+z+ 25% of time.
If left=x+y-z-, right=x-y+z+ 25% of time.
If left=x-y+z-, right=x+y-z+ 25% of time.
If left=x+y+z-, right=x-y-z+ 25% of time.

Because of symmetry, same numbers and probabilities as above.
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Elitzur-Vaidman problem

Bombs can have photon or light pressure triggers. Bombs explode if trigger does not jam, but jamming happens often. How can testers find at least one working bomb without exploding it {Elitzur-Vaidman bomb-testing problem} [1993] (Avshalom C. Elitzur and Lev Vaidman)? Using photon entanglement can find good bomb without triggering it.

teleportation

Particles can seemingly move from one place to another without ever being between the two places {teleportation}|. Teleportation requires that both locations share a particle pair {EPR pair}. Particles are identical, with entangled properties. For example, if one photon splits into two photons, new photons can be same-state superpositions. If instrument observes one particle's state later, it then knows other particle's state. If EPR pair exists, putting one pair member into one state can result in property disappearance at one location and other-pair-member property appearance at another location.

PHYS>Physics>Quantum Mechanics>Waves>Uncertainty

uncertainty principle

Instruments can measure momentum, position, energy, and time by absorbing energy and using clocks and rulers. However, instruments cannot simultaneously or precisely measure both particle momentum and position {uncertainty principle}| {Heisenberg uncertainty principle} {indeterminacy principle}, because measuring one alters information about the other. Instruments cannot simultaneously or precisely measure both particle energy and time, because they relate to momentum and position.

situation

The uncertainty principle is about measurement precision on one particle at one time and place. The uncertainty principle does not apply to different measurements on same particle over time. The uncertainty principle does not apply to simultaneous momentum and position, or energy and time, measurements on different particles.

wave packet

Particles have wavefunctions, so measurements are about wave packets. As particle moves through time and space, total uncertainty increases, because wave packet spreads out.

wave properties

Uncertainty follows from wave properties, because wave position and momentum, or time and energy, inversely relate. Energy and momentum depend on wave frequency. Position and time depend on wave amplitude. Measuring wave frequency or wavelength precisely prevents measuring wave amplitude precisely. Measuring wave amplitude precisely prevents measuring wave frequency or wavelength precisely. If momentum or position is specific, position or momentum must be uncertain. If energy or time is specific, time or energy must be uncertain.

At space points, wavefunctions that have high amplitude have precise position and timing. However, wavefunction slope is steep, so amplitude change between nearby points is large, so velocity change, momentum change, and energy change are large and so uncertain at that position. See Figure 1.

Wavefunctions with wide wave packets have large uncertainty. Wavefunction slopes are not steep, and amplitude change at nearby points is small, so velocity change, momentum change, and energy change are small in that region. Momentum is precise, while position is imprecise. Alternatively, energy is precise, while timing is imprecise. See Figure 2.

Waves that have just one frequency and wavelength have one momentum and energy. Only one wave can have no superposition and no cancellation anywhere in space or time, making wave equally present throughout all space and time, and so completely uncertain in position and time. See Figure 3.

Wavefunctions that have almost all frequencies and wavelengths have precise position and time, because waves cancel everywhere, except one space or time point. Wavefunctions that have almost all frequencies and wavelengths have almost all momentum and energy levels, making wave momentum and energy very uncertain. See Figure 4.

Waves that have some frequencies and wavelengths have moderate uncertainty in momentum and energy and moderate uncertainty in position and time, because waves cancel, except at moderate-size wave packet.

Waves with two or three frequencies and wavelengths have beat frequencies where waves superpose. Beat frequency makes precise momentum and energy, but time and position are uncertain. See Figure 5.

Waves with harmonic frequencies and wavelengths have beat frequencies where waves superpose. Beat frequencies make precise momentum and energy, but time and position are uncertain.

measurement processes

Besides wavefunction effects, physical processes limit precision. To find precise frequency for energy and momentum takes time and space, so position and time information are uncertain. To find precise position and time takes high amplitude, so position and time information are uncertain. Uncertainty's physical cause is discontinuity, whereas uncertainty's quantum-mechanical cause is wave-particle duality, because particles are about momentum and energy and waves are about position and time, as shown above.

mathematics

Quantum of action is h, and energy over time is action. Therefore, energy uncertainty dE times time uncertainty dt equals at least Planck constant divided by 4 * pi: dE * dt >= h / (4 * pi).

dE = F * dx = (dp / (4 * pi * dt)) * dx, so dE * dt * (4 * pi) = dp * dx. Position uncertainty dx times momentum uncertainty dp equals at least Planck constant: dx * dp >= h.

dx = 4 * pi * dF, and dp = dN / 2. Phase uncertainty dF times phonon number uncertainty dN equals Planck constant divided by 2 * pi: dF * dN = h / (2 * pi).

energy levels

Electrons in lower atomic orbitals have higher frequency, kinetic energy, and angular momentum and lower time period and orbital diameter. Electrons in higher atomic orbitals have lower frequency, kinetic energy, and angular momentum and higher time period and orbital diameter. Therefore, higher orbitals have higher position uncertainty and lower momentum uncertainty.

For low-orbital and high-orbital electrons, photon absorption can cause electronic transition to adjacent higher energy level, increasing position uncertainty and decreasing momentum uncertainty. For low-orbital and high-orbital electrons, photon emission can cause electronic transition to adjacent lower energy level, decreasing position uncertainty and increasing momentum uncertainty.

For low-orbital and high-orbital electrons, photon absorption can cause electronic transition to non-adjacent higher energy levels, increasing position uncertainty and decreasing momentum uncertainty. For low-orbital and high-orbital electrons, photon emission can cause electronic transition to non-adjacent lower energy levels, decreasing position uncertainty and increasing momentum uncertainty.

Besides fundamental Heisenberg uncertainty, electron, proton, and neutron configuration changes affect measured amounts. Electronic transitions conserve energy, momentum, and angular momentum, so absorption and emission do not necessarily have the same photon frequency. Electrons cannot transition to same orbital.

two particles

Though instruments cannot measure either's time or energy, instruments can measure two particles' energy difference and time difference precisely and simultaneously. Such measurement can define one-ness and two-ness.

confinement

By uncertainty principle, particles confined to smaller regions or times have greater momentum and energy. In confined regions, even in vacuum, energy is high, allowing particle creation and annihilation.

matrices

In quantum mechanics, particle position and momentum are quantized and so are matrices (not scalars or vectors), with complex-number elements. Because particles have probabilities of being anywhere in space, matrix rows and columns have infinite numbers of elements, and matrices are square matrices. In quantum mechanics, position and momentum are not necessarily independent, but depend on the whole particle system.

Matrices represent electronic transitions between energy levels. Matrix rows are one energy level, and matrix columns are the other energy level. Matrix elements represent the probability of that electronic transition. Matrix elements are periodic to represent the possible quanta. The diagonal represents transitions between the same energy level and so has value zero. Near the diagonal represents transitions between adjacent energy levels and so has higher values. Far from the diagonal represents transitions between non-adjacent energy levels and so has lower values. Energy levels have ground state and no upper limit, so the matrices have infinite numbers of elements. There is no zero energy level.

For non-infinite-dimension square matrices with real elements, PQ = QP (commutative). For infinite-dimension and/or non-square and/or complex-number-element matrices, PQ <> QP (non-commutative). Matrix multiplication is typically non-commutative.

In quantum mechanics, particle action is the product of the momentum P and position Q matrices: action = PQ. For infinite-dimension square matrices with complex-number elements, PQ - QP = -i*h*I, where I is identity matrix and h is Planck constant, because action has Planck-constant units and complex number multiplication rotates the axes by pi/2 radians.

Figure 1

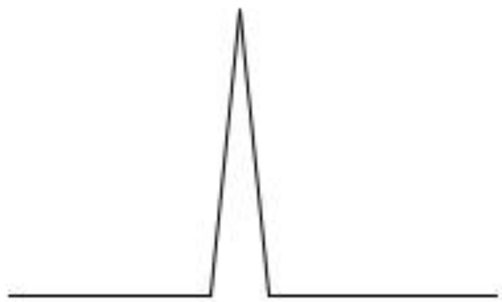
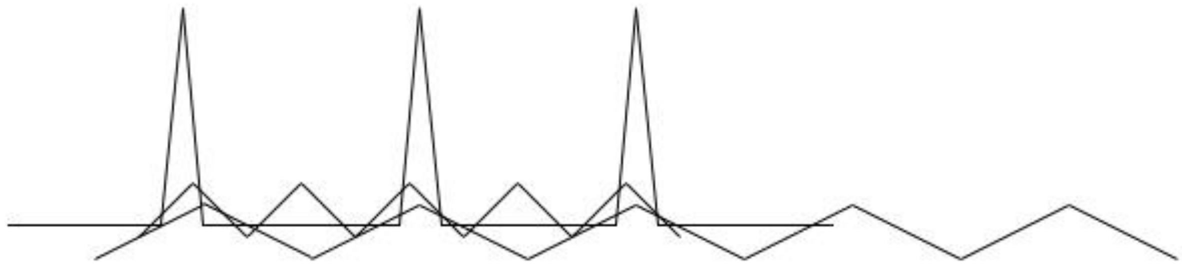


Figure 2

Figure 3

Figure 4

Figure 5



atom stability

Though electrons and protons have strong electrical attraction, and outside electrical attractions and repulsions can disturb atom orbitals, electrons do not spiral into protons and collapse atoms. Because particles have matter waves, by the uncertainty principle, orbiting electrons cannot spiral into atomic nucleus {atom, stability}. See Figure 1.

waves

Particles have matter waves, whose harmonic frequencies relate to particle energy levels.

uncertainty

Waves by definition must be at least one wavelength long. Therefore, particle waves have location uncertainty of at least one wavelength. Particle waves have time uncertainty of at least one period, which is one wavelength divided by light speed. Particle waves have momentum uncertainty of at least Planck constant divided by wavelength. Particle waves have energy uncertainty of at least Planck constant divided by period. Particle waves make the uncertainty principle.

energy

By uncertainty principle, particles must move, and so they cannot have zero energy. Particles cannot have zero energy because they cannot have zero motion, because that violates conservation of both energy and momentum. Lowest particle energy is first-quantum-level ground-state energy.

orbits

Electron orbits have quantum distances from nucleus and take quantum durations to orbit nucleus. In lowest orbital, electron position uncertainty has same diameter as orbital. Electron can be anywhere in that region around nucleus. In lowest orbital, electron time uncertainty is same period as orbital rotation. Electron can be anywhere in that interval. In lowest orbital, electron is already at closest possible distance and smallest possible time.

transitions

From lowest orbital, electrons cannot go to lower orbits, because there are no lower energy levels. They cannot lose more energy, because if energy decreases then time increases, by uncertainty principle, making orbital go higher. They cannot lose more distance because if distance decreases then energy must increase, by uncertainty principle, making orbital go higher. Therefore, lowest orbital has lowest energy, smallest distance, and shortest time. Lowest orbital already includes nucleus region, so it cannot be smaller.

kinetic and potential energy

In quantum mechanics and classical mechanics, electric-field positions relate to potential energies. In quantum mechanics, unlike classical mechanics, kinetic energy cannot completely convert to potential energy, and vice versa. Kinetic energy and potential energy have minimum energy level and cannot be zero.

energy quantum

First energy quantum is difference between ground-state energy and next-highest-orbital energy. Second energy quantum is difference between next-highest-orbital energy and third-orbital energy. Energy quanta are not equal. Energy quanta decrease at higher orbitals. Energy quanta relate to wave harmonic frequencies. Higher adjacent wave frequencies have smaller energy differences.

atom nucleus

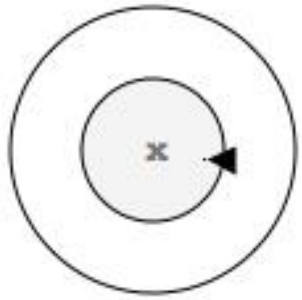
Atomic nucleus occupies only 10^-5 volume inside lowest-electron-orbital volume. Nucleus protons and neutrons have energy, momentum, position, and time uncertainty and so have ground-state energies. Nucleus protons and neutrons have quantum energy levels.

Lowest-orbital electrons and highest-orbital neutrons and protons never collide, because electrons have lower orbiting energies, and higher orbital radii, than neutrons and protons.

electron-proton collision

At high-enough energy and beam collimation, electrons can collide with atomic nuclei, because increased energy can narrow position, by uncertainty principle. Such electrons are not orbiting, so this situation is not about atom stability.

Figure 1



particle in box

Particle in enclosed space {particle in box} must have velocity, because particle has fixed position, so uncertainty is in momentum. If enclosed space is smaller, velocity must be more.

quantum fluctuation

Electric field and magnetic field cannot be at rest {quantum fluctuation}, because then they have precise position and precise zero momentum and so violate uncertainty principle. All fields have random motion, even in vacuum where net energy is zero.

vacuum polarization

At quantum level, empty-space field fluctuation {vacuum polarization}| is infinite.

Casimir effect

Two parallel uncharged metal plates attract each other by reducing vacuum-energy fluctuations and number of wavelengths between them {Casimir effect} {Casimir force}: energy density = c / d^4, where c is constant and d is plate distance. Energy at plate is zero. Interior energy density decreases, so exterior energy density increases and pushes plates together. Fewer particle histories with closed time-like loops are between plates.

zero point motion

Particles cannot be at rest {zero point motion}|, because then they have precise position and precise zero momentum and so violate uncertainty principle. All particles have random motion, even in vacuum where net energy is zero.

PHYS>Physics>Quantum Mechanics>Waves>Duality

wave-particle duality

For energy transfers, particles act like particles. For determining locations, particles act like waves {wave-particle duality}|.

complementarity in physics

Matter waves have spatial/momentum effects and time/energy effects, which instruments cannot detect simultaneously {complementarity, quantum mechanics}. Particles have energy, and waves have positions. Instruments cannot determine particle properties and wave properties simultaneously. Experiments can be only complementary, because particles always have both wave and particle properties.

PHYS>Physics>Quantum Mechanics>Waves>Experiment

two-slit experiment

Wave, photon, or particle sources can send collimated beams through one or two slits, to a measuring surface {slit experiment, quantum mechanics} {two-slit experiment}. For one slit, beam makes medium intensity line across from slit. For two slits, beam makes line with four times medium intensity across from slit. It makes alternating intense and clear lines on both sides. First intense line to side has two times medium intensity. Second intense line has medium intensity. Third intense line has lower intensity, and so on. Beam waves constructively and destructively interfere.

quanta

Particles sent through two consecutive pinholes create concentric rings on screen, as waves do. Particles sent through two adjacent pinholes make stripes perpendicular to line between pinholes on far screen, as waves do. If one slit closes, ring pattern appears. If slits alternate between closed and open, two ring patterns appear. If detector is at one slit, ring pattern appears. If detectors are poor, feeble stripe pattern appears. If half-silvered mirror is after one slit in particle-stream path, and both paths reflect from mirrors, stripe pattern appears.

wave

Particle motions are not single trajectories but diffract, as waves do. Wave theory accounts for all results. Matrix theory can account for results if slits act together to make periodicity.

Aharonov-Bohm effect

Paths entangle, so electrons that pass through beam splitter and go past solenoid coil have quantum interference {Aharonov-Bohm effect}, though no electromagnetic field is outside solenoid coil.

delayed-choice experiment

Detectors can be after location at which particles must choose which path to take and can turn on after particles pass decision point {delayed-choice experiment} (Wheeler) [1980].

quantum eraser

In two-slit experiments (Scully and Drühl) [1982], tagger {quantum eraser} can be in front of each slit to make spin clockwise or counterclockwise along axis. Screen can detect particle location and spin. There is no interference. Waves are present, but they cancel. Before screen, place spin tagger that always results in same spin. There is interference. Waves do not cancel.

down conversion

A photon can become two photons, each with half the energy {down-converter}. In beam-splitter experiments (Scully and Drühl) [1982], a down-converter can be on each path, to make one photon that continues on that path {signal photon} and one photon {idler photon} that is detected {delayed-choice quantum eraser}. Waves do not interfere.

When information about idler photon is random, because idler photon splits and goes on ambiguous paths, waves interfere. Instruments can receive the information before or after signal photons hit, by any amount of time or space. Waves are always present, but they can cancel.

detector

In two-slit experiments, particles make interference pattern when observed. If detector capable of knowing if particle went through left, right, none, or both slits is after slits, and it indicates that each particle goes only through either left or right slit, never both or none, there is no interference pattern.

If detector can operate without affecting particle in any way, and observer observes it, there is still no interference pattern.

If observer does not observe detector, there is interference pattern, even if detector puts the information in memory awhile and then deletes memory. This suggests that just gaining information is enough to end interference [Seager, 1999].

PHYS>Physics>Quantum Mechanics>Wavefunction

wavefunction

The quantum mechanics wave equation, which relates kinetic and potential energy to total energy, has complex-number, single-valued, continuous, and finite solutions {wavefunction}|. The wave equation, and its wavefunction solutions, are about abstract phase space, which includes space-time and describes system momenta and position or energy and time states. Wavefunctions represent possible physical-system energy levels and positions, and their probabilities. Wavefunctions correlate particle energies and times or particle momenta and positions. Wavefunctions typically depend on position, because energy includes potential energy. Wavefunctions typically depend on time, because energy includes kinetic energy. Wavefunctions are not physical waves and have no energy or momenta, but mathematically represent system properties.

Wavefunction is about infinite-dimensional abstract Hilbert space, in which wavefunction rotates as a unitary function and is deterministic.

energy and frequency

Because particle matter waves resonate in physical systems, wavefunctions have fundamental frequency and harmonics of fundamental frequency. System energy levels depend on wavefunction frequencies. System energy levels are discrete, and quanta separate energy levels. High-frequency waves have high energies. System boundary conditions set used or injected energy and wave fundamental frequency and harmonics of fundamental frequency.

amplitude, intensity, and probability

Wavefunction amplitudes are complex numbers that reflect physical-system position, time, energy, or momentum relations. Probabilities that particles are at locations depend on wavefunction amplitude for that location. Probabilities are linear and add, so probability of a set of states is sum of state probabilities. Wavefunction amplitudes can normalize, so sum of all state probabilities is one.

Intensity is absolute value of wavefunction-amplitude squared: wavefunction complex conjugate times position vector times wavefunction. Squared amplitude eliminates imaginary numbers and so is only real numbers. Absolute value makes only positive numbers. Intensities and energies are only discrete real positive numbers (eigenvalue). Amplitude squared absolute value relates to particle cross-section, collision frequency, and scattering-angle probabilities, and so to state probabilities.

wavelength

Waves have wavelength and so cannot be at a point but must spread over one wavelength. Particles have wave properties and can be at any point in region one-wavelength wide. Regions have wave amplitudes and so probabilities that particle is there.

resonance

In systems, reflected matter waves add constructively, and superpositions make standing-wave harmonic frequencies. Other frequencies cancel. Resonating fundamental wave has wavelength equal to system length or diameter and lowest-frequency. Fundamental-wave harmonic frequencies determine discrete possible particle energy levels.

deterministic

Wavefunctions are deterministic.

one particle

A one-particle system has a fundamental matter wave and its harmonics that determine possible particle positions and momenta. Harmonic wavefunctions are orthogonal/independent and linearly superpose. For particles with small momentum range and small position range moving along a straight line, wavefunctions are helices around the line with almost no amplitude at line ends and rising amplitude then falling amplitude near particle location.

one particle: definite momentum

For definite particle momentum along a straight line, position wavefunctions are helices around the line. If particle is at a well-defined position, helical waves have short wavelengths. If particle is at widespread positions, helical waves have long wavelengths.

one particle: no momentum

If particle has no momentum, momentum wavefunction is a straight line, and position wavefunction is constant.

one particle: definite position

For definite particle position along a straight line, momentum wavefunctions are helices around the line. If particle has high momentum, helical waves have short wavelengths. If particle has low momentum, helical waves have long wavelengths.

one particle: no position

If particle can be anywhere along a straight line, position wavefunction is a straight line, and momentum wavefunction is constant.

bound state

If energy times wavefunction, minus potential times wavefunction, is greater than zero, wavefunction oscillates {unbound state} {continuous spectrum}. Wavelength and quantum energy levels are too small to detect.

If energy times wavefunction, minus potential times wavefunction, is less than zero, wavefunction goes to zero {bound state} {discrete spectrum} only at special eigenvalues or else goes to infinity. At special eigenvalues, wavelength and quantum energy levels are large enough to detect.

eigenvalue

Wavefunctions are complex-number functions with complex-number solutions, but intensity has positive real values {eigenvalue, quantum mechanics}.

renormalization probability

Wavefunction amplitudes can adjust {renormalization, probability} {normalization, wavefunction}, so sum of all amplitude-square absolute values, or all energy-level probabilities, is 1 = 100%. Because systems have an infinite number of harmonic wavefunctions, without renormalization the sum of probabilities is infinite.

wavefunctional

In quantum field theory, generalized wavefunctions {wavefunctional} are about higher spaces {field space}.

series of electronic transitions

To find electronic-transition-series {series of electronic transitions} {electronic transition series} probability, multiply wavefunction complex-number amplitudes and then square product absolute value.

state vector

Abstract phase space describes system particle momenta and positions. Wavefunctions describe possible system particle positions and momenta states {state vector} {quantum state}. For example, in a system, a single particle has constant momentum and two possible positions. System has two (non-interacting) state wavefunctions, S1 and S2, with different probabilities depending on wave amplitude at the state, c1 and c2. Wavefunction W is sum of each state's amplitude times state wavefunction: W = c1 * S1 + c2 * S2. System wavefunction is a superposition of weighted state wavefunctions.

multiple particles

Particles have state wavefunctions at all possible positions and momenta. Particles can be independent or interact. If they are independent, particle wavefunctions multiply to make (linear) tensor products. Phase is not important for bosons, and tensor product commutes. Phase is important for fermions, and tensor product does not commute. If particles interact, system has entangled wavefunction.

unitary evolution

Over time, Schrödinger-equation wavefunctions can change deterministically {unitary evolution, wavefunction}, as position, time, energy, or momentum change.

PHYS>Physics>Quantum Mechanics>Wavefunction>Collapse

collapse of wavefunction

Isolated wavefunctions deterministically calculate future possible states. However, observing a particle measures particle position or momentum, putting particle into a definite phase-space state, and so cancels particle wavefunction {wavefunction collapse} {collapse of wavefunction}| {reduction of wave packet} {wave-packet reduction} {collapse of the wavefunction} {state vector reduction}. Wavefunction collapse is a discontinuity in physics. Collapse is time asymmetric. After observation, particle again has a wavefunction, until the nect observation.

observation and measurement

Observers and measuring instruments are too large to have observable wavefunctions, matter-wave wavelengths, matter-wave frequencies, or energy quanta. Observing and measuring cause particle interaction with a macroscopic system and make a new macroscopic system that includes the particle. Observers and instruments put particle wavefunctions into definite phase-space states {state preparation}, ready for measuring. Macroscopic systems have definite object positions and momenta.

Measuring requires that observer or instrument has definite phase-space state, and particle has definite phase-space state. Observers and instruments measure along one direction and detect particle position, time, momentum, angular momentum, or energy. Therefore, position, time, momentum, angular momentum, or energy observation/measurement operates on particle complex-number wavefunction and transforms it into a position, time, momentum, angular momentum, or energy real positive value. The value is any one of the set of possible different-probability quantum values (operator eigenfunction) described by the observer/instrument/particle wavefunction. State selection is completely random. Measurement results in a single value, not value superpositions or multiple values. The observer/instrument/particle wavefunction collapses to zero {measurement problem}. At measurement, particle phase-space state no longer exists, because particle wavefunction no longer exists.

operators

Measuring wavefunctions mathematically uses linear differential Hermitean operators.

causes

Measurements, absorptions, collisions, electromagnetic forces, and gravitational forces collapse particle wavefunctions. Gravitational effects can be gravitational waves, mass separation changes, gravitational self-energy changes, or fixed-star gravitational-field disturbances. Perhaps, measuring equipment is large and so affects wavefunction drastically (Bohr). Perhaps, collapse is large information gain (Heisenberg).

Perhaps, wavefunction collapse is due to particle and wavefunction properties. Perhaps, previous states have lingering wavefunctions that affect later wavefunctions. Perhaps, Gaussian wavefunction distributions coincide at random. Perhaps, wavefunctions have continual operators. Perhaps, wavefunctions are unstable every billion years {Ghirardi-Rimini-Weber} (GRW), so large masses collapse immediately (Giancarlo Ghirardi, Alberto Rimini, Tullio Weber).

Perhaps, wavefunction collapse is due to quantum mechanics. Perhaps, quantum fluctuations average {quantum averaging} to make definite energy states and space and time. Perhaps, cosmic inflation caused macroscopic-size quantum uncertainty and fluctuations {quantum uncertainty}.

wavefunctions and reality

Are wavefunctions just calculating devices, or do they exist in physical reality? Why do physical laws follow mathematical laws? How does perception relate to physical laws, mathematical laws, and material world? How does wavefunction collapse relate to physical laws, mathematical laws, and material world? How does wavefunction collapse relate to wavefunction time and space changes? How can observation/measurement and wavefunctions unify into a continuous explanation, rather than a discontinuous one?

alternatives: real wavefunctions

Perhaps, classical potential and quantum-mechanical potential both exist, so wavefunction is real. Measuring real wavefunction releases energy, starts wave fluctuations, and collapses wavefunction.

alternatives: undefined and defined states

Perhaps, particles have no wavefunction, so there is no collapse. Instead of wavefunctions, particles have only defined and undefined states. Undefined states can become one defined state. For example, particle density matrices represent possible different-probability physical states. Particle moves from undefined states to one state on the matrix diagonal. However, particles can be in superposed states, which matrices cannot represent. Particles can have only one or two possible states, which matrices cannot represent.

alternatives: subquanta

Perhaps, quantum levels involve even smaller properties, or quantities that cause them. However, particles have no hidden variables and so no subquanta.

alternatives: larger whole

Perhaps, physics has another conservation law about a larger whole. Observers and instruments measure only observable parts, while other parts are not observable. Whole system, observable and not observable, is deterministic, continuous, and time symmetric. For example, objects always travel at light speed, but some are time-like, and some are space-like. However, particles have no hidden variables and so no larger whole.

alternatives: two state vectors

Perhaps, quantum states have two phase-space state vectors, one starting from last wavefunction collapse and going forward in time and the other starting from next wavefunction collapse and going backward in time (Yakir Aharonov, Lev Vaidman, Costa de Beauregard, Paul Werbos) [1989]. Before and after phase-spaces are different. At events, forward-state vector happens first, and then backward-state vector happens. Their vector product makes density matrices, allowing smooth transitions between wavefunctions and collapses. This theory gives same results as quantum mechanics with one state vector. Forward and backward effects allow consistency with general relativity. However, time cannot flow backward, by general relativity.

alternatives: positivism

Perhaps, only measured results count, and wavefunctions are non-measurable things. However, experiments involving primitive measurements demonstrate that quantum state is deterministic and unique, so wavefunctions seem to have reality.

decoherence

Entangled particle wavefunctions depend on each other, maintain phase relations, and have coherence. In isolated systems with entangled particle wavefunctions, system wavefunction continues to evolve deterministically. In non-isolated systems with entangled particle wavefunctions, measurements, absorptions, collisions, electromagnetic forces, and gravitational forces disturb particles and cause entangled superposed particle states to become independent {decoherence}|. System wavefunctions become non-coherent, and particle waves no longer interfere with each other {decoherent histories}, though observers only know this afterwards. System-state phase-space vector reduces to zero. Each particle is independent and has one position and one momentum.

objective reduction

Non-local large-scale gravitational processes eventually collapse all system wavefunctions {objective reduction}. Particle systems cannot remain isolated, because universe gravitation is at all space points.

state distinction

For macroscopic systems without observers, macroscopic observation can separate states, so system states are distinct {state distinction principle} {principle of state distinction}.

PHYS>Physics>Quantum Mechanics>Wavefunction>Collapse>Non-Local

non-locality

Entangled particles stay in immediate and direct contact, by sharing the same system wavefunction, over any-size space or time interval {non-locality}|. Changes in one particle immediately affect the other particle, seemingly sending information faster than light speed. Conservation laws hold, because particle travels as fast as information, and same particle can go to both detectors. Perhaps, non-locality is due to quantum-mechanical space and time being discrete, foam-like, and looping.

action at a distance

Particles, energies, fields, and quanta are always in space-time. Physical objects and events happen only in space-time.

Wavefunctions are abstract non-physical mathematical objects that describe possible particle or system states and their probabilities. Particle and particle-system wavefunctions are not physical forces, are not energy exchanges, and are not objects in space-time. Wavefunctions describe all space-time points simultaneously. Waves have wavelength, and so are not about only one point, but all wave points at once. Wavefunctions account for and connect all space points, and so appear infinitely long.

As particles interact (and so form an interacting-particle system), the particle wavefunctions superpose to make a system wavefunction, in which all particle states depend on each other. Because wavefunctions connect all space, particles separated by arbitrary distances have states that affect each other. If one particle changes state, the other particle instantaneously changes state, no matter how far apart in space the particles are, because the system wavefunction (and all waves) collapse at all points simultaneously. Experiments that measure energy and time differences, or momentum and position differences, show that particles can remain entangled over far distances and long times, and that wavefunction collapse immediately affects all system particles, fields, and points, no matter how distant. (Because later times involve new wavefunctions, wavefunction collapse never changes particles at same place at different times.) State-vector reduction seemingly violates the principle that all physical effects must be local interactions, because coordinated changes happen simultaneously at different places.

Particle and system wavefunctions are about particles in indefinite states. Observation of one particle's definite state instantaneously collapses the system wavefunction and puts all system particles in definite states, no matter how far apart they are. No physical force or energy at the other particle causes the definite state, but the no-definite-state simultaneously changes to definite state {action at a distance}. The cause seemingly travels faster than light speed to make an effect. Therefore, the cause is non-physical.

Physical causes and effects must occur at one event in space-time. All physical communications, forces, and energies require local interactions through field-carrying particle exchanges in space-time. Physical interactions can have no action at a distance.

theories

Perhaps, wavefunctions reflect something physical that can account for action at a distance. Perhaps, particles can travel backward in time, from measured position to previous position, to make cause and effect at same space-time point. Perhaps, wavefunctions have retrograde wave components, so particles are always interacting at same space-time point. For example, in double-slit experiments, backward-flowing waves (from detectors to incoming particles) determine particle paths and explain whether wave or particle phenomena appear. However, general relativity does not allow time to flow backward. Furthermore, space-time points cannot have different times simultaneously.

theories: no-space-time

Perhaps, every space-time point touches an abstract outside-space-time structure. Perhaps, quantum foam has no-space-time in it. Perhaps, just as all sphere points touch sphere interior, all space-time points touch a no-space-time interior. By whatever method, every space-time point communicates with all others through no-space-time. No-space-time has no distances or time intervals, so space and time do not matter, and action at a distance can occur.

No-space-time is an abstract mathematical object, just as are quantum-mechanical waves. Perhaps, no-space-time carries quantum-mechanical waves.

Copenhagen interpretation

Before measurement, particles can be said to be everywhere {Copenhagen interpretation}|, not necessarily close to the observed position. Because particle is everywhere, measured particle is always adjacent to other system particles, so there is no non-locality.

Einstein-Podolsky-Rosen experiment

Spin-zero-particle decay can make two entangled coupled spin-1/2 particles, one +1/2 and one -1/2, which have one coherent system wavefunction {Einstein-Podolsky-Rosen experiment} {EPR experiment}. After particle-pair production, one particle always has spin opposite to the first, by conservation of angular momentum, but observation has not yet determined which particle has which spin. If an instrument detects one particle's spin direction and collapses the system wavefunction, the other particle immediately has the opposite spin, even over long distances. Einstein, Podolsky, and Rosen said instantaneous information transmission was impossible, so particles changed to the measured spins when the particles separated. Experiments showed that both particles have no definite spin until measured, so particles had superposed states until measured. By quantum mechanics, neither particle has definite spin-axis direction, so particles have superposition of +1/2 and -1/2 states until measured.

Experimenters must choose direction around which to measure spin and can measure in any direction. If they measure opposite direction, they can observe opposite spin. Therefore, particle production alone does not determine measured spin, and realism does not happen. Measuring system and particle together, as a new system, determine measured spin.

spin detection

If two spin-1/2 particles are in singlet state, three detectors oriented at -120, 0, and +120 degree angles perpendicular to moving-particle path can measure one particle's spin. Probability that both spins have opposite values is cos^2(A/2), where A is angle.

PHYS>Physics>Quantum Mechanics>Wavefunction>Collapse>Measurement

measurement level

Named things have unique values {nominal level} {level of measurement} {measurement level} {absolute, measurement}. Name and value have one-to-one correspondence. Origin and units do not matter.

Different named things have value differences {interval level}. Affine linear transformations, such as t(m) = c * m + d, where m is value and c and d are constants, maintain differences.

For many named things, values have positions {ordinal level} in order. Monotone increasing transformations maintain order.

Values have ratios {ratio level} {log-interval level}. Power transformations, such as t(m) = c * m^d, where m is value and c and d are constants, maintain ratios. Linear transformations maintain ratio relations.

measurement postulate

Interaction with matter collapses wavefunctions {measurement postulate}.

quantum mechanical measurement problem

How do wavefunctions, such as electron fields, collapse everywhere simultaneously {quantum mechanical measurement problem}. Collapse is absolute, with no relativity.

scale for measurement

Measurements can map directly to object properties {scale, measurement} {measurement scale}. Measurement relations can map directly to object-property relations.

superselection rules

Perhaps, measurement theory needs special prohibitions {superselection rules} on measurements.

PHYS>Physics>Quantum Mechanics>Wavefunction>Collapse>Measurement>Operators

observable in measurement

For objective measurement, events {observable} must be independent of where or when they happen. Objective measurements cannot be functions of space or time coordinates.

Measurements need reference points, such as x=0, and measurement units, such as meter. By relativity, objective measurements cannot be functions of reference points or units.

Measured state is orthogonal to all other possible states, because if one state happens, others do not. Measured state can be along coordinate {primitive measurement}.

Measurements in systems with no waves, or with waves with no phase differences, can have any order {commuting measurement}. Primitive measurements commute, because they are not about phase, only about yes or no. Measurements in systems with waves and phase differences depend on sequence {non-commuting measurement}. Most measurements do not commute, because they find value or probability.

subjective measurement

In quantum mechanics, time and space are not continuous but have quanta. In phase space, momenta relate to positions, and energies relate to times, so events are functions of space and time coordinates. Because positions and lengths relate to momenta, events are functions of reference points and units. Objective measurement is not possible. Quantum mechanics has only subjective measurement.

interaction

To measure particle size, light must have wavelength less than particle diameter and so high frequency and energy. High energy can change particle momentum. Higher energy increases momentum uncertainty.

To measure particle momentum, light must have low energy, to avoid deflecting particle, and so long wavelength. Longer wavelength increases location uncertainty.

Measuring position requires different-frequency light wave than measuring momentum, so experiments cannot find both position and momentum simultaneously (uncertainty principle).

wavefunction collapse

Measuring disturbs particle and creates a new system of observer, instrument, and particle, with a new wavefunction. At actual measurement, the new system wavefunction collapses to zero. Measuring allows observing only one particle property.

operator

Momentum, energy, angular momentum, space, or time functions {operator, wavefunction} operate on wavefunction to find discrete positive real values (eigenvalue) of momentum, energy, angular momentum, space, or time, which are all possible outcomes, each with probability. Direct measurements project onto space or time coordinate or energy or momentum vector.

direct measurement

Projection operators operate on wavefunction and project onto space or time coordinate, or energy or momentum vector, to give discrete positive real values (eigenvalue) {direct measurement}, which are all possible outcomes, each with probability. Experimenters can know possible measured values and predict probabilities. However, values may be less than quantum sizes and so not measurable. Operators have same dimensions as particle.

Alternatively, experimenters can prepare a quantum system in a known initial state, have particle interact with prepared quantum system, separate particle and prepared quantum system, and then measure quantum-system state {indirect measurement}. Indirect measurements require entangling particle and prepared quantum system, to couple their states. Wavefunction collapse puts quantum system into a state that indirectly determines particle state. Quantum system can have same or more dimensions as particle.

positive-operator-valued measure

Operators on wavefunctions produce discrete positive real values (eigenvalue) {positive-operator-valued measure} {positive operator-valued measure} (POVM).

projection operator for measurement

Operators {projection operator, measurement} on wavefunctions can project values onto measurement axis.