# Chapter 1

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# Coherence in the Physical World

## Microscale Coherence: The Phenomenon of Quantum Nonlocality

In the physical world the anomalous form of coherence has been much researched and discussed. It is quantum coherence—the coherence among the quantized packets of matter-energy known as quanta.

The curious behavior of quanta is legendary. The light and energy quanta that come to light in the famous physics experiments do not behave as the small-scale equivalents of familiar objects. Until an instrument or an act of observation registers them, they have neither a unique location nor a unique state.

The state of the quantum is defined by the wavefunction that encodes the superposition of all the potential states the quantum can occupy. When the quantum is measured or observed, this superposed wavefunction collapses into the determinate state of a classical particle. Until then the quantum has the properties of both waves and corpuscles, that is, wave-particle complementarity. And, as Werner Heisenberg's indeterminacy principle indicates, its various properties cannot be measured at the same time. When one property is measured, the complementary property becomes blurred, or its value goes to infinity.

The superposed state of the quantum defies realistic explanation. This state obtains between one deterministic quantum state and another in the absence of observation, measurement, or another interaction. This period in time—which varies from a millisecond in the case of a pion decaying into two photons, a uranium atom decaying after ten thousand years, to a photon that may reach the retina of the eye of a human observer after eleven billion years—is regarded as one tick of a fundamental quantum clock, or q-tick. According to the standard Copenhagen interpretation, reality does not exist during a q-tick, only at the end of it, when the wavefunction has collapsed and the quantum has transited from the superposed indeterminate to a classical determinate state.

It is not clear, however, what process brings about the collapse of the wavefunction. Eugene Wigner speculated that it is due to the act of observation: the consciousness of the observer interacts with the particle. Yet also the instrument through which the observation is made could impart the crucial impetus, in which case the transition occurs whether or not an observer is present. Heisenberg affirmed now the former view, now the latter (Heisenberg 1955, 1975).

That the wavefunction of particles would collapse upon interaction has been demonstrated in experiments first conducted by Thomas Young in the early nineteenth century. Young made coherent light pass through an intervening surface with two slits. He placed a screen behind the intervening surface in order to receive the light penetrating the slits. Then a wave-interference pattern appears on the screen. One explanation is that photons have the property of waves: they pass through both slits. This becomes problematic when the light source is so weak that only one photon is emitted at a time. Such a single packet of light energy should be able to pass only through one of the slits. Yet, when seemingly corpuscular photons are emitted one after another, an interference pattern builds up on the screen, and this could only occur if the photons are waves.

In a related experiment by John A. Wheeler, photons are likewise emitted one at a time; they are made to travel from the emitting gun to a detector that clicks when a photon strikes it (Wheeler 1984). A half-silvered mirror is inserted along the photon's path; this splits the beam, giving rise to the probability that one in every two photons passes through the mirror and one in every two is deflected by it. To confirm this probability, photon counters that click when hit by a photon are placed both behind this mirror, and at right angles to it. The expectation is that on the average one in two photons will travel by one route and the other by the second route. This is confirmed by the results: the two counters register a roughly equal number of clicks—and hence of photons. When a second mirror is inserted in the path of the photons that were undeflected by the first, one would still expect to hear an equal number of clicks at the two counters: the individually emitted photons would merely have exchanged destinations. But this expectation is not borne out by the experiment. Only one of the two counters clicks, never the other. All the photons arrive at one and the same destination.

It appears that the photons interfere with one another as waves. Above one of the mirrors the interference is destructive—the phase difference between the photons is one hundred eighty degrees—so that the photon waves cancel each other. Below the other mirror the interference is constructive: the wave-phase of the photons is the same and as a consequence they reinforce one another.

Photons that interfere with each other when emitted moments ago in the laboratory also interfere with each other when emitted in nature at considerable intervals of time. The "cosmological" version of Wheeler's experiment bears witness to this. In this experiment the photons are emitted not by an artificial light source, but by a distant star. In one experiment the photons of the light beam emitted by the double quasar known as 0957 + 516*A,B* were tested. This distant quasi-stellar object is believed to be one star rather than two, the double image due to the deflection of its light by an intervening galaxy situated about one fourth of the distance from Earth. (The presence of mass, according to relativity theory, curves space-time and hence also the path of the light beams that propagate in it.) The deflection due to this "gravitational lens" action is large enough to bring together two light rays emitted billions of years ago. Because of the additional distance traveled by the photons that are deflected by the intervening galaxy, they have been on the way fifty thousand years longer than those that came by the more direct route. But, although originating billions of years ago and arriving with an interval of fifty thousand years, the photons interfere with each other just as if they had been emitted seconds apart in the laboratory.

It turns out that, whether photons are emitted at intervals of a few seconds in the laboratory, or at intervals of thousands of years in the universe, those that originate from the same source interfere with each other.

The interference of photons and other quanta is extremely fragile: any coupling with another system destroys it. Recent experiments indicate that when any part of the experimental apparatus is coupled with the source of the photons, the fringes that record the interference vanish. The photons behave as classical particles.

For example, in experiments designed to determine through which of the slits a given photon passes, a “which-path detector” is coupled to the emitting source. As a result the fringes weaken and ultimately vanish, indicating interference. The process can be calibrated: the higher the power of the which-path detector, the more of the fringes disappears. The experiment conducted by Mordechai Heiblum, Eyal Buks, and their colleagues at the Weizmann Institute in Israel made use of a device less than one micrometer in size, which creates a stream of electrons across a barrier on one of two paths (Buks et al. 1998). The paths focus the electron streams and enable the investigators to measure the level of interference between the streams. With the detector turned on for both paths, the interference fringes disappear as expected. But the higher the detector is tuned for sensitivity, the less interference patterns there are.

It appears that a physical factor enters into play: the coupling of the measuring apparatus to the light source. This coupling is closer than one would expect: in some experiments the interference fringes disappear as soon as the detector apparatus is readied—even when the apparatus is not turned on. Leonard Mandel’s optical-interference experiment bears this out (Mandel 1991). In Mandel’s experiment two beams of laser light were generated and allowed to interfere. When a detector is present that enables the path of the light to be determined, the fringes disappear. They disappear regardless of whether or not the determination is actually carried out. It appears that the very possibility of "which-path-detection" destroys the superposed-state of the photons.

This finding was confirmed in experiments carried out in 1998 at the University of Konstanz (Dürr et al. 1998). In these experiments the puzzling interference fringes were produced by the diffraction of a beam of cold atoms by standing waves of light. When there is no attempt to detect which path the atoms are taking, the interferometer displays fringes of high contrast. However, when information is encoded within the atoms as to the path they take, the fringes vanish. Yet the instrument itself cannot be the cause of the collapse—it does not deliver a sufficient "momentum kick." The back action path of the detector is four orders of magnitude smaller than the separation of the interference fringes. In any case, for the inference pattern to disappear the labeling of the paths does not need to be actually determined by the instrument: it is enough that the atoms are labeled so that the path they take *can* be determined.

These experiments can be performed whether or not anyone is watching; consequently they do away with the theory that a conscious observer is needed to collapse the wavefunction. And they also show that measurable physical interaction is not a necessary condition of the collapse: it also occurs in its absence.

A similar kind of intrinsic correlation among particles comes to light in the so-called EPR (Einstein-Podolski-Rosen) thought-experiment put forward in 1935 (Einstein, Podolski, Rosen 1935). In this experiment a particle is split in two, and the two halves are allowed to separate and travel a finite distance. Then a measurement is made of one aspect of the quantum state of one of the halves—such as the spin state—and a measurement of another aspect of the state of the other. Einstein proposed that since the quantum states of the particles are identical, we would then know both aspects of their state at the same time. This would show that the Heisenberg indeterminacy principle does not yield a complete description of physical reality.

When in the 1980s experimental apparatus sophisticated enough to test Einstein's thought experiment became available, it turned out that measuring, for example a spin component of particle A has an instantaneous effect on particle B: it causes B's spin wavefunction to collapse into a state with the opposite spin component (the permissible spin states are "up" or "down" along axes *x*, *y*, and *z*). Particle B manifests different states when different measurements are made on particle A—the effect depends on just what is measured on A. Thus the measurement on A does not merely reveal an already established state of B: it actually *produces* that state. Somehow, A "knows" when B is measured, and with what result, for it assumes its own state accordingly.

There appears to be a nonlocal connection between particles A and B. Empirical experiments first performed in the early 1980s by Alain Aspect and collaborators, and frequently repeated since then, show that this connection is intrinsic to the particles, and is not due to signals transmitted by the measuring apparatus (Aspect et al. 1982, Aspect & Grangier 1986, Selleri 1988, Duncan & Kleinpoppen 1988, Hagley et al. 1997, Tittel et al. 1998). The experiments involved more particles over ever-larger distances, without modifying these results. It appears that separation does not divide particles from each other. It is not necessary that the particles should have originated in the same quantum state; experiments show that any two particles, whether electrons, neutrons, or photons, can originate at different points in space and in time—they remain correlated as long as they had once assumed the same quantum state, that is, were part of the same coordinate system.

The results can be extrapolated to show that the correlations between quanta are invariant in regard to distance and time. Quanta that at one time and one place occupied the same quantum state can be light years apart in space and thousands of years apart in time, and still remain correlated.

Space- and time-transcending correlations are not explained by the assumption that a finite-velocity (even if supraluminal) signal would connect the particles. The quantum state appears to be intrinsically nonlocal. Already in his 1935 assessment of the EPR experiment Schrödinger maintained that particles in the quantum state do not have individually defined states: their states are fundamentally "entangled" with each other. The state of collective superposition applies to two or more properties of a single particle, the same as to a set of several particles. It is not the single particle or the single property of a particle that carries information on the quantum state, but the collective wavefunction of the system of coordinates in which the particles participate.

A mathematical specification of the collective state of particles within a given quantum system was furnished by Ke-Hsueh Li of the Chinese Academy of Sciences (Li 1992, 1994, 1995). He has shown that the Heisenberg uncertainty principle is an alternative approach to grasp the coherence properties of fields and particles. According to Li, interference between different probability amplitudes, and hence the coherence property of probability packets, must be understood in reference to "coherence space-time." Coherence time is the time within which interference between the packets exists, and coherence length (or volume) is the space within which such interference occurs. Coherence space corresponds to the breadth of the wave function which is the region within which matter (more exactly, matter-fields) and radiation (force-fields) are statistically distributed. Interference patterns are formed only within coherence space-time; beyond it, phase information is lost. Within coherence space-time supraluminal velocities can occur and nonlocality is the rule. Particles and fields constitute one indivisible whole.

Although the nature of nonlocality and entanglement are not yet definitively determined, it is already clear that these phenomena exist and make for a remarkable space- and time-transcending form of coherence among quanta. The quantum world is entirely hallmarked by this coherence—a major element in what Richard Feynman dubbed the "central mystery" of physics.

## Macroscale Coherence: The Phenomenon of Cosmic Nonlocality

The kind of coherence observed in the domain of the quantum was believed to be limited to that domain; the world of macroscopic objects was thought to be "classical." Yet this assumption is no longer entirely true. There is growing evidence that an anomalous form of coherence also occurs at macroscopic scales; indeed, even at cosmic scales. The whole universe, it appears, has coherence-features that suggest that it is nonlocal (Nadeau 1999). The standard model of the universe, the cosmology of the Big Bang, cannot account for this finding.

Big Bang cosmology maintains that the universe originated in an explosive instability in the quantum vacuum. A region of this pre-space exploded, creating a fireball of staggering heat and density. In the first few milliseconds it synthesized all the matter that now populates space-time. The particle-antiparticle pairs that emerged from the vacuum collided with and annihilated each other; and the onebillionth of the originally created particles that survived (the tiny excess of particles over antiparticles) made up the matter-content of the universe we now observe. After about two hundred thousand years these particles decoupled from the radiation field of the primordial fireball: space became transparent, and clumps of matter established themselves as distinct elements of the cosmos. Due to gravitational attraction they condensed into gigantic swirls that solidified as galaxies. In time these became further structured as stars and stellar systems.

The overall features of Big Bang theory's "standard scenario" are well established; the computer analysis of some three hundred million observations made by NASA's Cosmic Background Explorer satellite (COBE) in 1991 provided confirmation. Detailed measurements of the cosmic microwave background radiation—the presumed remnant of the Big Bang—show that the variations derive from the original explosion and are not distortions caused by radiation from stellar bodies. They are the remnants of minute fluctuations within the cosmic fireball when it was less than one trillionth of a second old. They indicate the amount—if not the nature—of the particles of matter that were created (and not quasi-immediately annihilated) in the universe. If the surviving particles make for a matter-density above a certain number (estimated at $5 \times 10^{-26}$ $g/cm^3$), the gravitational pull associated with the total amount of matter will ultimately exceed the inertial force generated by the Big Bang and the universe is closed: it will collapse back on itself. If matter-density is below that number, expansion will continue to dominate gravitation—the universe is "open"; it will expand indefinitely. However, if matter-density is precisely at the critical value, the forces of expansion and contraction will balance each other and the universe is “flat.” It will remain balanced at the razor’s edge between the opposing forces of expansion and contraction.

Recent findings disclose aspects of the universe that are unexpected, if not entirely anomalous. In light of the standard model, for example, the “Boomerang” (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) project’s observations of the microwave background in 1999—observations that covered only 2.5 percent of the sky but that achieved a resolution thirty-five times higher than that of COBE—are truly surprising: they indicate that the universe is precisely flat. This finding was impressively confirmed by a number of increasing sophisticated observations: by MAXIMA (Millimeter Anisotropy Experiment Imaging Array) as well as by DASI (Degree Angular Scale Interferometer, based on a microwave telescope at the South Pole), and most recently by WMAP (Wilkinson Microwave Anisotropy Probe, a satellite that has been orbiting the Earth since June 30, 2001 and recording cosmic radiation from a point on the far side of the moon). It is now beyond reasonable doubt that the Big Bang was fine-tuned to the staggering precision of one part in $10^{50}$! A deviation even of that minute order would have produced an infinitely expanding or a finite recollapsing universe.

Not only is the matter-density of the universe precisely tuned for balance between expansion and contraction; the universe’s forces are also precisely tuned to the parameters of its matter particles. As Arthur Eddington and Paul Dirac already observed, the ratio of the electric force to the gravitational force is approximately $10^{40}$, while the ratio of the observable size of the universe to the size of the electron is likewise around $10^{40}$. This is strange, because the former ratio should be unchanging (both forces are believed to be constant), whereas the latter should be changing (since the universe is expanding). If the agreement of these ratios, the one variable the other not, is more than a temporary coincidence, as Dirac suggested in his “large number hypothesis,” the force of gravitation is not constant over time. Moreover when Einstein’s mass-energy relation is applied, the size of the electron ($ro = 6 \cdot 10^{-15}$ meters) turns out to be a consequence of the number of electrons in the visible universe (this is Eddington’s number, approximately $2 \times 10^{79}$ in the Hubble universe of $R = 10^{26}$ meters).

Menas Kafatos and his collaborators showed a relationship between the masses of the total number of particles in the universe to the gravitational constant, the charge of the electron, Planck's constant, and the speed of light (Kafatos 1989, 1990, 1999). Scale-invariant relationships appear—for example, all lengths turn out to be proportional to the scale of the universe. This suggests a staggeringly high level of coherence throughout the cosmos—according to Kafatos et al. the entire universe is nonlocal.

The coherence of the universe is also manifest in the fine-tuning of its basic parameters. The universal forces and constants are precisely tuned to the evolution of complex systems, including those associated with life. A minute difference in the strength of the electromagnetic field relative to the gravitational field would have prevented the evolution of systems of higher complexity since hot and stable stars such as the Sun would not have come about. If the difference between the mass of the neutron and the proton would not be precisely twice the mass of the electron, no substantial chemical reactions could take place. Similarly, if the electric charge of electrons and protons did not balance precisely, all configurations of matter would be unstable and the universe would consist of nothing more than radiation and a relatively uniform mixture of gases.

However, in this universe the gravity constant ($G = 6.67 \times 10^{-8}$) is precisely such that stars can form and shine long enough to allow the evolution of complex galactic structures in space, as well as of complex microstructures on the surface of planets associated with hot and stable stars. If $G$ would be smaller, particles would not compress sufficiently to achieve the temperature and the density needed to ignite hydrogen: stars would have remained in a gaseous state. If on the other hand $G$ were larger, stars would have formed but would burn faster and endure for a shorter time, making it unlikely that complex structures could evolve on the planets surrounding them. Likewise, if the Planck constant ($h = 6.63 \text{ x } 10^{-27}$ *erg*) would be even minutely other than it is, carbon-producing nuclear reactions could not occur in stars—and consequently complex structures based on carbon-bonding could not arise on otherwise suitable planetary surfaces. Given the actual value of $G$ and $h$, and of an entire array of other universal constants (including the velocity of light, the size and mass of the electron, and the relationships between the size of the proton and the nucleus), the universe could evolve to the level of complexity we now observe (Barrow & Tipler 1986).

An additional feature of the coherence of the cosmos comes to light in the uniformity of the cosmic background radiation as well as of the galactic macrostructures. The microwave background radiation, emitted when the universe was about a hundred thousand years old, is known to be isotropic. But at the time the radiation was emitted the opposite sides of the expanding universe were already ten million light years apart. Light could only have traveled a hundred thousand of these light years—yet the background radiation (at 2.73 degrees on the Kelvin scale) is uniform throughout the presently observed universe. Moreover distant galaxies and macrostructures evolve in a uniform manner although they are not connected by physical signals, and have not been so connected since the first few microseconds in the life of the universe. If a galaxy ten billion light years from Earth in one direction exhibits structures analogous to a galaxy the same distance away in the opposite direction, then structures that are twenty billion light years from each other are structurally uniform. This cannot be ascribed to physical factors, since according to general relativity the highest rate at which signals can propagate in space-time is the speed of light, and light could reach across the ten-billion light-year distance from Earth to each of the galaxies (hence we can observe them), but it cannot reach from one of these galaxies to the other.

A sophisticated mathematical account of this "horizon problem" is furnished by the theory of cosmic inflation originally advanced by Alan H. Guth (Guth 1997). According to the cosmic inflation theory also elaborated by Andrei Linde, at the initial Planck-time of $10^{-33}$ seconds the cosmos expanded at a rate faster than light. This did not violate general relativity, since it was not matter that moved at these velocities, but space itself—matter (the particles that were the first to be synthesized) stood still relative to space. During inflation all parts of the universe were in immediate contact, sharing the same density and temperature. Subsequently some parts of the expanding universe fell out of contact with each other and evolved on their own. Even if light did not catch up with the circumference of the expanding universe (because the universe's circumference became larger than the distance light could have traveled during the corresponding time), all of its structures could evolve uniformly: they were connected during inflation.

Whether or not coherence in the current universe is adequately explained by inflation theory is as yet open to question. Cyclic models of the universe can explain all the facts accounted for by inflation theory based on one period of acceleration per cycle rather than a superfast acceleration followed by the relatively moderate acceleration of the Robertson-Walker universe. Moreover, we shall argue, cyclic models of the universe can be developed to offer an explanation of the observed fine-tuning of the universe's physical constants, whereas inflation theory cannot explain why the universe that arose in the wake of the Big Bang is such that it could produce complex structures, including the self-maintaining structures associated with life.

The puzzle is the selection of the vacuum fluctuations preceding the Big Bang. This is not likely to have been a random selection, since the fluctuations came in specific varieties, a small subset of all the varieties that were theoretically possible. The statistical probability that the varieties that had actually occurred would have come about purely by accident is negligibly small. According to calculations by Roger Penrose, the probability of hitting on a universe such as ours by randomly sifting through the alternative possibilities is of the order of one in $10^{10^{123}}$.

But perhaps our remarkably coherent universe did not arise in a randomly unordered vacuum pre-space, but in a vacuum ordered by prior cosmic history. The history of the cosmos may extend beyond the Big Bang: a growing number of investigators entertain the possibility that this universe arose in the context of a preexisting metauniverse or *metaverse* (Rees 1997, Steinhardt & Turok 2002). In part 2 we shall look at this scenario in more detail, since it may offer a logical explanation of the large-scale coherence of the universe we now observe.