On the Empirical Premises of Modern Physics

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Abstract

Physics relies on experimental evidence. However, the discipline's view of reality is essentially theoretical, for data without interpretation is without meaning. Thus, the verity of theorized reality remains a matter of consent when we cannot relate to it through our own experience, regarded as the fundamental source of knowledge. Even with calculations matching data, there is no guarantee that the mathematical model maps one-to-one onto reality. Moreover, unlike one based on an axiom, an effective theory is amenable to tuning and extending. Such models with parameters lacking correspondence to physical substance are inapt for falsification, as modern physics' renowned conceptual conundrums and persistent problems might imply. To free ourselves from this convenient yet confounding instrumentalism, I reexamine from a common-sense perspective some of the iconic experiments that paved the way to relativity theory and quantum mechanics. In light of the century-long success of modern physics using fitting yet impenetrable concepts, such as spacetime, wave-particle duality, and entanglement, my approach in explaining phenomena in tangible terms may seem obsolete. However, I find the proposed naïve realism hard to refute since calculations agree with measurements and the axiomatic basis seems solid.

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1. Introduction

Modern physics, i.e., quantum mechanics and relativity theory, chiefly concerns very low or high temperatures, very short or long distances, or great velocities. If we cannot liken phenomena under extreme conditions to our first-hand experience, we cannot ascertain the tenet empirically. Moreover, unlike a theory based on an axiom, an effective theory, i.e., a mathematical model of data, cannot be falsified with the data it was made to model.

The truth of modern physics would hardly be an issue had not its interpretations portrayed reality at odds with common sense. How could one particle take two paths simultaneously? How could a measurement of one particle immediately disclose the corresponding property of another one? How could gravity be just sheer geometry since we sense its presence by our own body?

Even in all its opacity, I am not questioning modern physics itself, only attempts to interpret mathematical models as something real, for they were never meant to be taken as something real. As Niels Bohr's aide Aage Petersen summarized his master's view: "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature..." [1].

Be that as it may, we have a hard time abiding by Bohr, for we are disposed to make sense of what we see. Clear causation rather than indecipherable description encapsulates an explanation [2]. The antirealistic stance is, per definition, unnatural if not problematic in practice. What is the point of regarding theories as mere instruments for trending data? What is the purpose of using concepts that do not qualify as candidates for verity or falsity? Is not science supposed to reveal truths, the things that could not be different?

Such concerns seem naïve, perhaps even idealistic, implying that nature would be comprehensible in all its intricacies. On the other hand, power laws, nearly log-normal distributions, logarithmic spirals, and even characteristics of chaos found across scales and scopes [3] suggest the unity of nature [4] in conformity with everyday experiences; hence comprehensible in its entirety.

Since scrutinies over decades have not cleared conceptual conundrums up, perhaps even muddled them up, say, by logically extending superposition from particles into parallel universes [5], let us go back and reexamine in the light of experience few iconic experiments that led to modern physics. While such an exercise may seem outdated, even contemptuous of the pioneers' legacy, time has put things in perspective. By now, measurements have substantiated thought experiments to precision beyond any doubt. There is no excuse, no escape, but we confront the repercussions of instrumentalism [6].

Given the in-depth discourse on conceivable loopholes, ambiguities in interpretations, and experimental uncertainties associated with the legendary experiments that are seen to validate spacetime, wave-particle duality, and entanglement, the paper at hand may seem superficial and shallow. However, the real issue is not an incomplete acknowledgment of prior papers but whether the proposed common-sense perspective makes sense of not just one but several key experiments that led to modern physics. In the spirit of science, even a single piece of empirical evidence would be enough to prove the offered tenet wrong, but none have been found so far. In contrast, no number of affirmative arguments, in addition to those provided below, would exhaust all possibilities and suffice to prove it right.

2. Spacetime

The four-dimensional manifold, the geometry of relativity, as a model of gravitation seems consonant with observations, at least when disregarding data that call for dark matter and dark energy. Perhaps these elusive quintessences suggest that the substance of space should not be discounted despite the evidence against the ether hypothesis. Moreover, as modern physics does associate the vacuum state with some essence, namely, quantum fluctuations, could such a successful model, so to say, an ephemeral and undetectable relativistic ether [7-9], correspond to an all-embracing physical substance?

2.1 The Michelson−Morley experiment

In brief, Michelson and Morley sought in 1887 to show that the vacuum transmits light like air sound but did not detect the earth moving relative to such a medium, the ether [10]. Instead, light traveled just as fast along the two interferometer arms, one parallel and the other perpendicular to the motion.

While there is no sign of the luminiferous ether to this day, its once posited presence has not been much of a concern since special relativity (1905). The theory stems from the very postulate consonant with the observations: the speed of light in the vacuum does not depend on the speed of either the light source or the observer. So, numbers square with data. Still, it is somewhat disturbing that we do not know why the speed of light is the same in any inertial frame.

After Einstein generalized (1915) his theory to accelerating motion, e.g., a falling body, the curved spacetime concurred with a wealth of data. Still, the ontology of space and time troubled Einstein [11, 12]. Sheer geometry agrees with measurements but does not explain gravity or inertia [13]. Moreover, are fleeting quantum fluctuations, transient particle-antiparticle pairs, virtual particles [14-16] without firm essence truly veritable, i.e., verifiable account of the vacuum energy density, electromagnetic properties, and black-body spectrum? Could the observations, against all odds, be understood in testable and tangible terms?

2.2 The substance of space

Let us open up an empirical perspective to the vacuum by perceiving it as light instead of the luminiferous ether, the old abandoned light-mediating medium. At first sight, the suggestion may seem strange. How could the vacuum comprise light yet be transparent?

We have learned by experience that light does not glance off a lens coated with a thin film of quarter wavelength thickness when rays reflect from the lens and film combine in an out-of-phase manner. However, does the destructive interference force the paired photons themselves to vanish into nothingness or only their electromagnetic fields to cancel each other out? Is the number of photons truly a non-conserved quantity?

In the words of Maxwell, after he related the speed of light to the permittivity and permeability of the vacuum, "We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena." [17]. Faraday, too, had considered lines of force, i.e., gravitational, electric, and magnetic fields, themselves to be the substance of space [8].

However trivial it may be, the paired-photon substance makes sense because the speed of light in the vacuum comprising light could not be other than the speed of light, as

Maxwell imagined and Michelson and Morley discerned. Also, the passage of light in light could not differ from the least-time path, the geodesic outlined by general relativity, as Einstein inferred and Eddington determined.

Importantly, the proposed paired-ray plenum (Fig. 1) conforms to the vacuum's characteristic spectrum, the black-body radiation [18, 19]. As S. N. Bose reasoned, after deriving Planck's law of radiation, a large number of photons n_i, over all photons n, distributes on energy levels, E_i, relative to the average energy, $k_B T$, as

$$\frac{n_i}{n} = \frac{2}{e^{E_i/k_B T} - 1}, \tag{1}$$

where the factor 2 counts for the two allowed polarizations [20]. As part of a paired-photon ray, a photon can oscillate either in-phase or out-of-phase with its neighboring photons (Fig. 1).

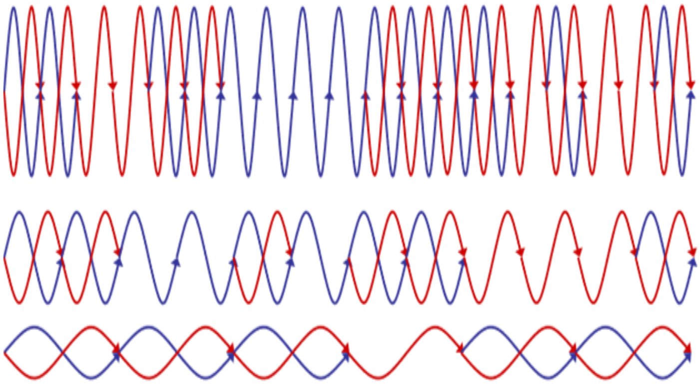

Fig. 1. When out of phase, light rays of paired photons (blue and red) cannot be seen as light because they cancel each other's electromagnetic effects. Nevertheless, their density remains present and perceptible as gravity and inertia. In contrast, odd photons (blue or red), distributed among the paired rays, embody readily detectable electromagnetism.

The phase-space element of the paired-photon vacuum holds the content h^3, as Bose wrote to Einstein [21] after considering Planck's constant $h = Et$ as the measure of a photon having energy E and period t its complementary attributes. In line with Planck's law, the pairs open up with increasing temperature, and conversely, the photons pair up with decreasing temperature. From this perspective, the paired-photon rays form an all-embracing lattice akin to the quantum chromodynamics (QCD) vacuum. In this light, Maxwell's hydrodynamic derivation of his famous equations makes perfect sense; the Lorenz gauge is not just a gimmick to deal with mathematical redundancy in the field variables [22] but a continuity condition that equates flows of the vacuum with its density changes [23].

The quantized vacuum is understood to underlie the Casimir effect [24, 25] and the dynamic Casimir effect, where real photons are thought to materialize from virtual photons [26]. However, could not the photons, as they appear two by two at a time, emerge out of the paired-photon vacuum? Likewise, the photons are thought to materialize in response to an imposed electric field. Again, however, could not the external field force the photons out from the pairs to produce the vacuum polarization?

It is worth recalling that the current comprehension, however successful, is not exactly free from complications. For example, unobservable vacuum fluctuations, the postulated transient particle and antiparticle pairs, yielding permittivity and permeability consistent with measurements, are troubled with unrealistic energy [27, 28].

The proposed paired-photon vacuum may seem speculative, for, at first sight, unfamiliar seems speculative just as relativity theory and quantum mechanics one time did. But the aim is not confrontation rather concurrence. From the proposed perspective, both spacetime, as a mathematical manifold without explicit essence, and the quantum vacuum, as a pool of virtual particles, are excellent models of the physical vacuum comprising photons in pairs.

The main thing is whether there is any empirical evidence that falsifies the paired-photon conjecture. For example, if photons were to appear out of nothingness or to disappear into nothing or if a photon were to break apart, then the atomistic axiom underlying the paired-photon vacuum would be false. Moreover, since physicists demand verifiable predictions to vindicate claims, let us inspect the substance of space in the cosmological context.

2.3 The substance of gravity

After expanding for t = 13.8 billion years, the void's energy density $\rho \approx 0.6 \cdot 10^{-9}$ J/m^3, gauged by the Wilkinson Microwave Anisotropy Probe [29], holds only about 0.1‰ radiation [30]. So, could the paired-photon substance make the most?

Feynman offered that the void embodies the gravitational potential of all mass M, as it is hardly a coincidence that the void's energy density ρ is almost, if not exactly, equal to the mass density [31] $\rho_M = 1/4\pi Gt^2 = \rho/c^2 \approx 7 \cdot 10^{-27}$ kg/m^3. Integrating the density over the age of the universe t to $GMM/R = Mc^2$ gives an estimate for the total number quanta $n = 10^{121}$ from the total action $nh = Et = c^5t^2/G$ of the universe, expanding at the speed of light $c = R/t$. This inference resonates with Gilbert N. Lewis' suggestion that everything comprises quanta of light; hence the light quantum deserves the atomistic name, the photon [32, 33]. Newton himself had reasoned likewise when querying, "Are not gross bodies and light convertible into one another?" [34]

Logically, the void's total energy equals the energy bound in all matter as it sums up all gravitational potentials of which each tallies the mass of a body. Then it is clear that the universal balance is a persistent property, not a contemporary cosmic coincidence. It implies that the void emerges from matter rather than out of nothingness. When reasoning that matter fuels the expansion, the density of matter could not be but critical and the universe's geometry could not be but flat [29]. In other words, nuclear reactions in stars, akin to annihilation, transform quanta of elementary particles into visible photons and flows of paired quanta of light. Indeed, by all accounts, the universe is consuming matter on its way to heat death, the state of ever diluting photon gas, comprising light quanta also in pairs. In this way, the cosmic expansion is understood as a physical transformation [35], not only modeled through the cosmic scale factor.

The proposed physical vacuum is not a new idea. Already Riemann and Yarkovsky had reasoned that gravitation is a manifestation of the void in motion toward universal and local balance[36, 37]. Bodies couple by their mass to the flows of space rather than the bodies themselves having a propensity to attract each other or repel. For instance, as stated by Hubble's law, distant galaxies can be understood to recede due to influxes of space, i.e., paired quanta, originating from numerous transformations in the vast universe. Conversely, nearby galaxies can be understood to approach due to effluxes of quanta emerging from relatively few transformations in the Local Group. According to astronomical observations, the influxes and effluxes balance at about four million light years, R_o [38-40]. Out there, the efflux going through the zero-velocity surface at R_o from the processes consuming the mass, M_o, within the local galaxy group equals the influx coming from the processes exhausting the total mass, M, within the radius of the universe, $R = GM/c^2$.

A paired photon (Fig. 1), as a massless spin-2 particle, is indistinguishable from the carrier of gravitation, the theorized graviton embodying the densities and fluxes of energy and momentum [41]. This substance of gravity is isotropic but not homogenous because it extends from the dense distant past to the sparse present. Thus, in local balance with matter throughout the universe, the paired-photon density displays a gradient that gives rise to a tiny acceleration $a = GM/R^2 = c/t$, ca. 10^{-10} m/s^2, across all of space. Consistently, it has been inferred that the universal density gradient due to all ordinary matter manifests itself in the rotation and velocity dispersion of galaxies in a law-like manner [42, 43]. From this ontological outlook, both modified gravity [44] and dark matter [45] are excellent models but not explanations of the feeble universal gravitation arising from the expansion from the dense past to the sparse present.

The uniformity at the largest scale, i.e., the evenness of cosmic background radiation and the isotropic distribution of distant galaxies, is customarily ascribed to cosmic inflation. However, it can be understood to follow from the least-time quest for balance. This is to say, to flatten out differences causation across the horizon is not necessary; a common cause is. Namely, Newton's 2nd law states: the larger the force, i.e., the difference in energy, the faster it decreases. Thus, for example, the most massive stars, including supermassive black holes, consume matter fastest. Conversely, the smallest stars, red dwarfs, glitter eons. By the same token, there will be only minute energy differences over time, irrespective of how immense the early variations in density were, as observed [46]. Thus, in harmony with the Copernican principle, the nearby universe is the sparsest spot as it is the oldest locus seen from our perspective.

Newton refuted action at a distance, so did Einstein, however, without substantiating the argument. Now the puzzle comes to nothing. The paired-photon vacuum is all around hence reacts as if instantaneously to any perturbation. While inertia is felt immediately, it still takes time for the vacuum to regain balance after a change as perturbations spread all over at the speed of light. Such variations in the density of the void, i.e., gravitational waves [47], manifest themselves as fluctuations in the vacuum's refractive index $n^2 = GM/c^2R = 1$, as Einstein thought early on [48]. A Lorentzian ripple in spacetime, as if shortening and stretching arms of a gauging interferometer [49], is an apt but not accurate model of the variation in optical length, the tangible density wave.

The paired-photon vacuum as the relativistic ether [50] expresses Mach's very idea: mass out there is the cause of inertia here. So then, centrifugal force is not a fictitious force [51] to be explained away by a coordinate transformation but a real effect imposed by the vacuum in balance with distant stars. Indeed, the most distant matter contributes most to the vacuum energy, i.e., the universal gravity, because the number of galaxies increases with distance as r^2 whereas the gravitational potential decreases as $1/r$. The overall effect increases with r [13]. In other words, not a single body bears a chance to be at odds with the vacuum in balance with all bodies. For example, while it is true that a spinning top straightens up after being poked because angular momentum is conserved, the profound reason for the conservation is that the top is immersed in the plenum of paired-photon rays that assume their least-time paths anew. For the same reason, a spiral galaxy and its satellites realign in a common plane after perturbation [52].

While we can, for example, infer from blueshifts and redshifts that the earth is moving along with the Milky Way relative to the rest, we should also explain in substance why the cosmic microwave background appears slightly warmer in the direction of movement than in the opposite direction [53]. Likewise, while the cosmic expansion can be modeled using the time-dependent scale factor $a(t)$, via the definition of the Hubble parameter $H(t) \equiv a_t(t)/a(t)$, the embodiment of time ought to be clarified too.

From the physical viewpoint, the universe ages through expansion $H(t) = 1/t$, as the photon periods lengthen, i.e., frequencies shift to red [23, 35, 54], for energy and time do not exist as such without substance. Thus the logical conclusion is that the flow of light quanta embodies the flow of time as the photons carry energy on their periods (of time).

I wish to stress that the proposed physical vacuum is a testable thesis. For example, a ray of light bends in the paired-photon embodied gravitational field consistently with gravitational time-delay measurements, however, about five times more than the lensing given by general relativity [55]. So from this viewpoint, there is no need for dark matter. The discrepancy between the precise gravitational time-delay measurements and the famous lensing observation stems from Eddington ignoring the parallax between the rays from a distant star observed during the eclipse and measured from the night sky [55].

Moreover, the aforementioned shallow density gradient from the sparse present to the dense distant past explains the galaxy rotation curve and velocity dispersion without dark matter [43]. Also, perihelion, geodetic, and frame-dragging precessions calculated by the principle of least action agree with data [35, 56]. Furthermore, according to the least-time principle, angular diameter distance is a monotonic function, i.e., the object appears the smaller, the further away it is [35]. In contrast, in the standard cosmology, the expansion lenses the object counterintuitively ever larger beyond the redshift $z = 1.25$.

Finally, there is no need for dark energy. When calculated by the least-time principle, the intensity and redshift of a ray of light from a distant supernova through the universe expanding at the decelerating rate $H = 1/t$ agrees with data [55]. The conclusion does not rest on the tired light hypothesis [57] but follows from acknowledging both the recessional and gravitational redshifts due to the diluting density of the expanding universe.

In summary, the paired-photon vacuum offers a falsifiable empirical premise to fathom both experiments and observations reproduced by modern physics.

3. The wave-particle duality

According to quantum mechanics, particles display also wave characteristics and waves also particle properties depending on the circumstances. Yet, despite reproducing data, the wave-particle duality contrasting everyday experience remains profoundly incomprehensible. So, could the duality, however instituted and ingrained, be partitioned into particles and the paired-photon vacuum surrounding the particles?

3.1 The double-slit experiment

In 1927, Clinton Davisson and Lester Germer observed that electrons scatter from a crystal the way waves reflect from a grating. The diffraction pattern was seen to prove Louis de Broglie's hypothesis that particles are like waves.

No question, fringes on the detector screen are reproduced through calculation assuming matter waves of length $\lambda = h/p$ and momentum p stream from slits and interfere with each other. However, does the mere resemblance of a calculated with an observed pattern qualify as an explanation? Is the particle truly a wave, or is the vacuum that undulates around the particle?

The wave-particle duality is not only a strange concept [58] but, strangely enough, even when only one photon passes through the slits at a time, the calculation presumes that the slits are flooded with light. Feynman was concerned about this clash between theory and reality: "Of course, actually there are no sources at the holes. In fact, that is the only place that there are certainly no sources. But, nevertheless, we get the correct diffraction pattern by considering the holes to be the only places where there are sources." [59] Does the counterintuitive instrumentalism work because the vacuum bristles with light, i.e., photons in pairs?

3.2 The wavy vacuum

An empirical perspective on the interference phenomena opens up when we take into account the all-pervading physical vacuum. For example, a moving particle generates vacuum waves, which, when acting back on the particle, cause interference (Fig. 2). Similarly, the waves of a boat, when reflected back, rock the boat. And analogously, the waves of a bouncing oil droplet, when reflected back, interfere with the droplet [60, 61].

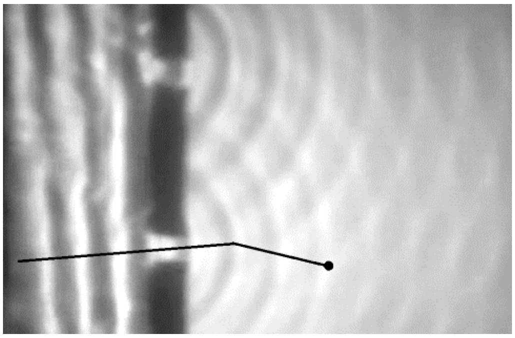

Fig. 2. A moving particle (dot) produces waves of the vacuum that go through the two slits and strike back the particle and hence cause an interference phenomenon.

We are familiar with wave phenomena and fathom, for example, that the mere act of observing which way the particle is going [62], by blocking waves or giving rise to ripples, disturbs or even washes out the interference pattern. Further, we know that obstacles such as poles placed at nodes do not perturb the wave pattern, as the Afshar experiment demonstrated [63-65]. At the points of destructive interference, where the electromagnetic field vanishes [66], there are no single photons apart from thermal ones, but there could be paired photons. Such a zero of an optical field is familiar, for example, from singular optics. The existence of a pattern with zeros, for example, emerging from a single slit, could be probed by a tiny obstacle and inferred from the splittings it introduces.

Given the proposed paired-photon vacuum, the wavefunction can be understood as a theoretical concept that accounts for the vacuum undulating around the particle rather than the particle itself. Accordingly, like waves in a denser medium, the waves of a denser vacuum, e.g., under an intrinsic or applied electromagnetic potential, are shorter. Therefore a phase difference develops over a path compared to the ground-state vacuum, as the Aharonov−Bohm experiment exposed [67-69].

The concept of wave-particle duality [70] can thus be understood so that the field is the dual of the particle. Theoretically speaking, the vacuum without particles rests at the ground state, whereas it exists at an excited state when strained by particles. For example, due to its charge, magnetic moment, and mass, an electron is surrounded by characteristic electric, magnetic, and gravitational fields. In geometric terms, the rays of the photon-embodied vacuum diverge, curl, and compact around the electron in line with Maxwell's hydrodynamic view of the vacuum.

In hindsight, the perplexing duality, amalgamating a wave and a particle, was needed since we do not directly experience an elementary particle or a bigger body but through the vacuum. For example, to see the electron itself, we would have to extract at least one quantum, a neutrino, out of it rather than out of its field, but that act would break the electron apart and turn it into a W^- boson [71]. In concord with Heisenberg's uncertainty principle, no measurement can be more precise than one quantum because the object changes upon observation at least by that amount.

3.3 Wheeler's delayed-choice experiment

In 1978, John A. Wheeler conceived a thought experiment where a photon, having gone through a beam splitter, is thought to "have decided" to behave either as a particle or wave, but while still on its way, it is made to reverse its "decision" by placing another beam splitter in front of the detector or removing it from there (Fig. 3) [72, 73]. The delayed-choice outcome has been verified experimentally [74]. However, in line with prior inference, the experiment does not undermine a realistic view of the quantum state [75].

From the empirical perspective, the experiment involves the photon and the waves it generates in the surrounding paired-photon vacuum. Theoretically speaking, these waves embody photon self-energy [16]. The photon-associated waves, customarily modeled with the wave function [76], obey wave mechanics, say, the Fresnel−Arago laws. In the absence of the second beam splitter, the waves cross perpendicularly and do not interfere; in the presence of it, they end up running in parallel and do interfere. Hence, the photon does not "decide" anything. Instead, the experimenter chooses by introducing the second beam splitter to detect the interference. This common-sense conclusion that the second beam splitter has no delayed effect on the photon but merely influences its subsequent evolution has been substantiated earlier [77].

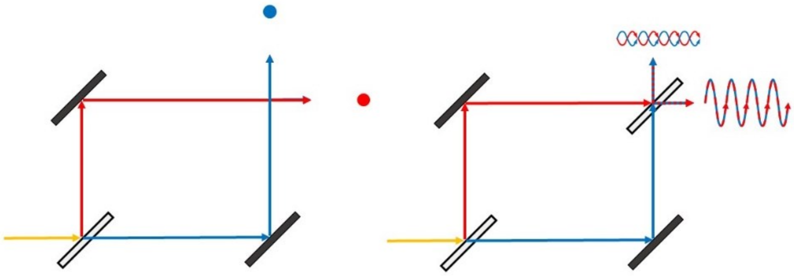

Fig. 3. (Left) A photon either goes through (blue) a beam-splitter or gets reflected (red). Then it goes on and gets reflected straight to one port of the detector or to the other. Thus, Wheeler argued the photon decided to behave as a particle. (Right) When another beam splitter is put in front of the detector, a destructive interference pattern develops on one port and a constructive on the other. Thus, Wheeler maintained that the photon had reversed its decision and behaved as a wave. However, it is not only the photon that propagates from one mirror to another but also the waves of the vacuum to which the photon propagation gives rise.

The delayed-choice experiment highlights the difficulty of thinking that the light quantum would be, on the one hand, a localized particle and, on the other, an extended wave [78, 79]. The concern does not expire by redefining photons and particles as extraordinary entities, say quantons, uniting the dual aspects [80]. By contrast, it makes sense that a photon, just as a particle, perturbs the surrounding paired-photon vacuum yet is distinct from it. The perturbation is known as the field.

Also, the two-photon correlation evinced by Hong, Ou, and Mandel [81] is easy to absorb when acknowledging the photon-accompanied vacuum waves. Moreover, the wavy vacuum is almost at the fingertips when gripping a glass of water firmly, as the fingerprints become visible through an evanescent wave despite the total internal reflection. The evanescent wave is not only a mathematical necessity of continuity at an interface but a physical phenomenon because the vacuum is at an excited state next to a surface. The vacuum's excitations, local anomalies, are also known as quasiparticles, such as holes in semiconductors, and collective excitations, such as phonons and plasmons, in solids and fluids.

After all, the key experiments that paved the way to modern physics can be understood when considering the all-embracing paired-photon vacuum.

4. Entanglement

According to quantum mechanics for correlated particles, the measurement of one particle reveals the corresponding property of the other instantaneously. Thus, while mathematically impeccable, entanglement is inexplicable. However, the observations can be understood by reexamining what is actually measured.

4.1 Aspect's experiment

Einstein, Podolsky, and Rosen considered an experiment where the inspection of one particle in a pair is thought to expose at once the corresponding property of the other [82]. If this were truly the case, they argued, the property must have a definite value before either one of the two is measured to challenge Bohr and Heisenberg, maintaining that the property does not have a value until measured.

While Carl Kocher carried out the actual experiment in 1967 [83] and Stuart Freedman and John Clauser in 1972 [84], Alain Aspect and his colleagues [85] are often recognized for providing an unambiguous demonstration of the quantum entanglement in 1982 that refutes Einstein's stance. Namely, for a pair of photons originating from radioactive decay, determining the phase of one photon revealed that of the other without delay. Even so, it has been shown that the correlation does not entail any form of non-locality when viewed from a relational perspective of quantum mechanics [86]. More importantly and contrary to common beliefs, the measured correlation matches the outcome of classical physics [87, 88]. Here I arrive at the selfsame conclusion.

As the photons set off having the opposite phases to balance momentum, the observed correlation, as such, does not ascertain entanglement or action at a distance because the phases, while correlated, remain undefined relative to the detector phases until detected. It is the cosine correlation between the two photons that physicists take as the proof of the incomprehensible entanglement, as they expect a linear correlation. For example, the correlation is 0.71 when the phase between the two detectors is 45 °, whereas physicists tend to think that it should be 0.50 by classical physics because photons with random phases are as likely (50% / 50%) to register in one as in the other of the detectors' two counters. However, this expectation is unwarranted.

4.2 The phase concept

An empirical aspect opens up to the correlation by perceiving a photon entering one or the other polarization-sensitive channel of a detector in the same way as you would go through one or the other door opening on either side of a corner (Fig. 4). For example, when viewed from the 45 ° angle, about 71%, not 50%, of each is visible, whereas when viewed straight ahead, one opening is fully visible (100%) and the other not at all (0%). Thus, when a beam splitter, such as a polarizer cube, is pivoted relative to the other, the phase-sensitive area open for the photon varies in a sinusoidal manner. So, the correlation of the photons follows the cosine instead of the commonly but erroneously assumed linear function.

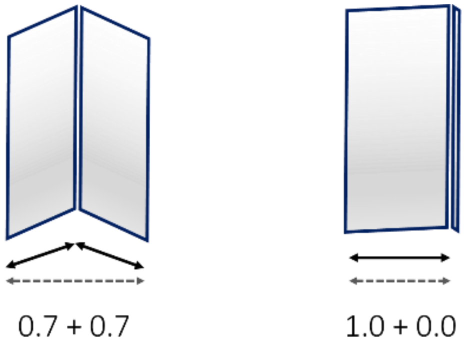

Fig. 4. When the phase-sensitive areas of a two-channel detector are at the angle of 45 ° relative to the photon phase, the photon wavelet enters one or the other channel with the probability of 71% compared to the situation when one channel is fully visible (100%) and the other not at all (0%).

The two-photon correlation $E = (N_{xx} - N_{xy} - N_{yx} + N_{yy})/(N_{xx} + N_{xy} + N_{yx} + N_{yy})$ is recorded from a large number of coincident photons N having random phases that entered either the x-channel or the y-channel of the A detector and those of the B detector (Fig. 5). For example, N_{xy} signifies the number of photons recorded pairwise on the A detector's x-channel and the B detector's y-channel.

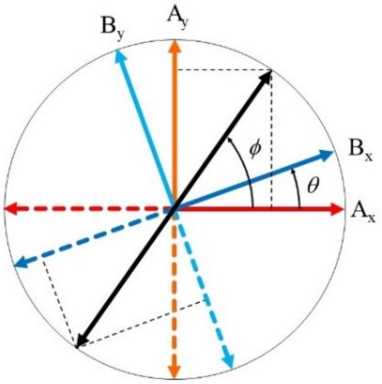

Fig. 5. Correlation is established in measurement in which two photons out-of-phase (black arrows) are captured by two-channel detectors (A and B). The detector channels are perpendicular ($A_x \perp A_y$ and $B_x \perp B_y$) and the corresponding channels of the two detectors (A_x & B_x and B_y & A_y) are at an angle θ relative to each other. The probability of one photon with phase ϕ entering the A detector channel A_x is $\cos\phi$ and on the channel A_y $\sin\phi$. The probability of the other photon with phase $\phi + \pi$ entering the B-detector channel B_x is $\cos(\phi + \pi - \theta)$ and on the channel B_y $\sin(\phi + \pi - \theta)$.

For a large number of coincident photons, the angle ϕ between the photon phase and the receiver phase varies randomly; thus, the correlation, E, can be calculated from the integral over all angles

$$\begin{aligned} E = \frac{1}{2\pi}\int_0^{2\pi} &[\cos\phi\cos(\phi + \pi - \theta) - \cos\phi\sin(\phi + \pi - \theta) \\ &- \sin\phi\cos(\phi + \pi - \theta) + \sin\phi\sin(\phi + \pi - \theta)]\,d\phi \\ &= \frac{-1}{2\pi}\int_0^{2\pi}[\cos\theta + \sin(\theta - 2\phi)]\,d\phi = -\cos\theta \end{aligned} \tag{2}$$

where θ is the angle between the corresponding channels of the two detectors. In case the photons emerge with orthogonal polarization as from spontaneous parametric down-conversion, the result is shifted by $\pi/2$. Conversely, were the two photons without phases relative to each other until measurement, a rotator turning polarization by an angle δ would not shift the correlation as $\cos(\delta - \theta)$.

As the calculation shows not only quantum but also classical covariance is the inner product $\mathbf{a} \cdot \mathbf{b} = |a||b|\cos\theta$ of the two polarizer axes, say, **a** for one detector setting (Alice) and **b** for the other (Bob). Since the classical calculation matches the data, spooky action at a distance and entanglement seem speculative [87], as does entanglement between photons that never coexisted [89].

The same conclusion was inferred recently by recognizing that Bell's inequality assumes erroneously for the classical probability that the experiment would be frame-independent [90-92]. In reality, phase is a frame-dependent property. So, Bell's theorem was refuted; the correlation does not stem from a non-local influence but particles sharing a parameter, not a hidden one but a relative one, i.e., having opposite phases [93]. Also, macroscopic entanglement of two oscillators [94, 95] can be understood as a correlation rather than implying non-locality or superluminal causation. Similarly, two clocks running at the same rate but set off by 12 hours are correlated but not causally connected; checking the time of one reveals at once the time of the other.

As a polaroid plate is pivoted, the projection of the photon phase, i.e., $\cos\theta$, governs the photon's passage through the phase-sensitive entrance, while the photon's energy, i.e., intensity proportional to $\cos^2\theta$, triggers its registration at the counter. In other words, one should not mistake the correlation coefficient, $r = \cos\theta$, denoting covariance in counts between the two detectors, for the expectation value, i.e., coefficient of determination, r^2, defining variance in counts of one detector that is predictable from counts of the other.

When the photon polarization is detected instead of the photon phase ϕ, i.e., ϕ is not distinguished from $\phi \pm \pi$, the correlation varies at a double rate and with half amplitude, i.e., $\frac{1}{4}(\cos2\theta+1) = \frac{1}{2}\cos^2\theta$, a form familiar from Malus' law.

All in all, Aspect's experiment does not prove entanglement, let alone action at a distance. The classical outcome could not but violate Bell's inequality. In hindsight, the persistent obscurity is rather peculiar as phase-sensitive or quadrature detection, i.e., $\cos\phi + i\sin\phi$, has been a routine matter in correlation spectroscopy for a long time [96].

The long-lasting miscomprehension about the two-photon correlation, leading to the erroneous expectation of a linear correlation and invented interpretation of non-locality, might also stem from perceiving the sum of probabilities as a normalized constant (100%). Surely, each detector registers photons with 100% probability irrespective of their phases, i.e., $\cos^2\phi + \sin^2\phi = 1$. However, the photon's probability of going through the polarizer one way or the other depends on the phase, i.e., vector, not a scalar. Likewise, while we have learned to hold heads and tails equally probable, the experience of tossing a weighted coin reveals right away that probability is a physical measure.

4.3 Causality

The mantra that correlation does not imply causation applies to Aspect's experiment. In contrast, a force whatsoever is a cause of a change in motion, and a change whatsoever in motion is a consequence of a force, as Newton declared in the preface of *Principia*. For example, a photon is a force carrier, having energy on its period. Ontologically, a flow of energy entails a flow of time because photons carry both energy and time [97]. Paraphrasing Leibniz, if we cannot tell the difference between time and a photon period, we must hold them the same. Time comprises periods as a trek comprises legs [23].

Even though the equation for the flows of quanta can be written down, it cannot be solved in general, only in a stationary state because the flows draw from driving forces, which in turn affect the flows, and so on [18]. When everything depends on everything, the motion is neither deterministic nor indeterministic (random) but non-deterministic.

Mathematically speaking, the boundary conditions, such as limits of integration, keep changing along with the changing system because the quanta that depart from the system arrive at the surroundings and vice versa. Thus, evolution is intractable, non-holonomic, path-dependent, but not all arbitrary. The future is genuinely open as much as there is free energy to drive changes of state. Only at the perfect balance trajectories are fully computable.

On the one hand, this holistic tenet about causality, compatible with our experience, contrasts eternalism, theoretically speaking, the block universe where space and time are on equal footing [98]. On the other hand, the realistic stance also differs from presentism since the present results from the forces present in the past. Unmistakably, history is on display everywhere.

In contrast to the evolving reality, quantum mechanics is geared up to model stationary systems where quanta, h, circulate closed trajectories, as the formal solution $\Psi(t) = \exp(-iEt/\hbar)\Psi(0)$ to the Schrödinger equation $i\hbar\partial_t\Psi = \hat{H}\Psi$ states. When nothing happens, symmetry holds and unitary operators, $\hat{H}$, suffice. Energy in a stationary system is conserved, i.e., the Hamiltonian of quantum mechanics is invariant. Thus, the acausal formalism cannot handle the breaking of symmetry, a spiraling trajectory, loss or gain of energy, E, and the concomitant change in time, t, which are associated with any event, say, measurement—hence the measurement problem.

5. Discussion

The presented common-sense comprehension of the renowned experiments of modern physics is posited on the revised photon concept. Instead of being merely the quantum of the electromagnetic field, the photon is seen as the fundamental building block of everything [32]. The axiom renders the proposal falsifiable. It takes only to show that the photon is non-conserved, i.e., decays or disappears into nothingness or emerges out of it. This stance contrasts the virtual photon or fleeting quantum fluctuation, instrumental concepts that are, per definition, not detectable, hence untestable. Juxtaposing instrumentalism with realism stresses the purpose of science, whether it is to model out a trend from the data or provide a viewpoint, a theory, that makes sense of the data.

While experiments cannot lie, their interpretation is a matter of inference. Empiricism is not free of some reasoning, rationalism. That is not a problem, but instrumentalism accompanied with dogmatism would be. Since physics is regarded as an empirical discipline on which other areas of knowledge are grounded, the foundations had better hold. Truths ought to be recognized as those things that could not be different.

Customarily, modern physics is employed to model microscopic and cosmic phenomena, but reality seems a seamless unity. Scale-free patterns, most notably power laws, are found everywhere [3, 99]. They have been understood to follow from the least-time consumption of free energy [4], also known as the principle of least action in its original open form [100, 101] derived from the atomistic axiom using statistical physics of open quantized systems [18]. In this light, arguments drawing from experience, however straightforward, are seen as valid and concepts traceable back to the axiom, however ordinary, as consistent.

When an outcome went against expectations, such as that of the Michelson−Morley experiment, physicists were not truly free from the then doctrine by adopting the opposite stance. Likewise, the model of cosmology was revised for the accelerated expansion rather than reconsidered when Type 1a supernovae data did not fit the anticipated decelerating expansion—acknowledging falsification failed [55, 102, 103].

Even in the face of a seemingly small setback, the substantial success of a prevailing thought style[104] is no guarantee of its validity and verity. We cannot even judge how good our best theories are [105-107], for the whole data could be understood even more accurately by another tenet [108, 109]. It seems that we do not recognize the gravity of discrepancies because an effective theory, unlike one based on an axiom, hardly offers opportunities for falsification but plenty for tinkering. Thus, the issues with modern physics are not whether its calculations match data but whether it was founded on premises that could be judged right or wrong. As Kuhn pointed out, quantitative analysis is sought in science, but paradoxically the goal of science is not achieved by measuring [110].

References

1. McEvoy, P., Niels Bohr: Reflections on Subject and Object. Microanalytix, (2001)
2. Salmon, W.C., Causality and Explanation. Oxford University Press, (1998)
3. Newman, M.E.J.: Power laws, Pareto distributions and Zipf's law. Contemp. Phys. 46 (5), 323 (2005) doi:https://doi.org/10.1080/00107510500052444
4. Mäkelä, T., Annila, A.: Natural patterns of energy dispersal. Phys. Life Rev. 7 (4), 477 (2010) doi:https://doi.org/10.1016/j.plrev.2010.10.001
5. DeWitt, B.S.: Quantum mechanics and reality. Phys. Today 23 (9), (1970)
6. Chakravartty, A., In The Stanford Encyclopedia of Philosophy, ed. by E.N. Zalta Metaphysics Research Lab, Stanford University (2017)
7. Barone, M.: The Vacuum as Ether in the Last Century. Found. Phys. 34 (12), 1973 (2004) doi:10.1007/s10701-004-1630-5
8. Nersessian, N.J., Faraday to Einstein: Constructing Meaning in Scientific Theories. Martinus Nijhoff Publishers, (1984)
9. Meschini, D., Lehto, M.: Is Empty Spacetime a Physical Thing? Found. Phys. 36 (8), 1193 (2006) doi:10.1007/s10701-006-9058-8
10. Capria, M.M., Pambianco, F.: On the Michelson-Morley experiment. Found. Phys. 24 (6), 885 (1994) doi:10.1007/BF02067653
11. Illy, J.: Einstein teaches Lorentz, Lorentz teaches Einstein their collaboration in general relativity, 1913-1920. AHES 39 (3), 247 (1989)
12. Lehmkuhl, D.: Why Einstein did not believe that general relativity geometrizes gravity. Stud. Hist. Philos. Sci. Part B 46, 316 (2014) doi:https://doi.org/10.1016/j.shpsb.2013.08.002
13. Sciama, D.W.: On the origin of inertia. MNRAS 113 (1), 34 (1953) doi:10.1093/mnras/113.1.34
14. Mainland, G.B., Mulligan, B.: Polarization of Vacuum Fluctuations: Source of the Vacuum Permittivity and Speed of Light. Found. Phys. 50 (5), 457 (2020) doi:10.1007/s10701-020-00339-3
15. Heisenberg, W., Weisskopf, V., In Early Quantum Electrodynamics: A Sourcebook, Cambridge University Press Cambridge (1994)
16. Schwinger, J.: Quantum Electrodynamics. II. Vacuum Polarization and Self-Energy. Phys. Rev. 75 (4), 651 (1949) doi:10.1103/PhysRev.75.651

17. Maxwell, J.C., The Scientific Letters and Papers of James Clerk Maxwell: Volume 1, 1846-1862. Cambridge University Press, Cambridge (1990)
18. Annila, A.: Natural thermodynamics. Physica A 444, 843 (2016) doi:https://doi.org/10.1016/j.physa.2015.10.105
19. Grahn, P., Annila, A., Kolehmainen, E.: On the carrier of inertia. AIP Advances 8 (3), 035028 (2018) doi:10.1063/1.5020240
20. Bose, S.N.: Plancks Gesetz und Lichtquantenhypothese. Z. Phys. 26 (1), 178 (1924) doi:10.1007/BF01327326
21. Venkataraman, G., Bose and His Statistics. Universities Press, (1992)
22. Rovelli, C.: Why Gauge? Found. Phys. 44 (1), 91 (2014) doi:10.1007/s10701-013-9768-7
23. Tuisku, P., Pernu, T.K., Annila, A.: In the light of time. Proc. Math. Phys. Eng. Sci. 465 (2104), 1173 (2009) doi:https://doi.org/10.1098/rspa.2008.0494
24. Casimir, H.B.G.: On the attraction between two perfectly conducting plates. Proc. K. Ned. Akad. Wet. 51, 793 (1948)
25. Stange, A., Campbell, D., Bishop, D.: Science and technology of the Casimir effect. Phys. Today 74 (1), (2021)
26. Wilson, C.M., Johansson, G., Pourkabirian, A., Simoen, M., Johansson, J.R., Duty, T., Nori, F., Delsing, P.: Observation of the dynamical Casimir effect in a superconducting circuit. Nature 479 (7373), 376 (2011) doi:10.1038/nature10561
27. Sciama, D.W., In The Philosophy of Vacuum, ed. by S. Saunders, H.R. Brown Oxford University Press Oxford (1991)
28. Rugh, S.E., Zinkernagel, H.: The quantum vacuum and the cosmological constant problem. Stud. Hist. Philos. Sci. Part B 33 (4), 663 (2002) doi:https://doi.org/10.1016/S1355-2198(02)00033-3
29. Hinshaw, G., Larson, D., Komatsu, E., Spergel, D.N., Bennett, C.L., Dunkley, J., Nolta, M.R., Halpern, M., Hill, R.S., Odegard, N., Page, L., Smith, K.M., Weiland, J.L., Gold, B., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Tucker, G.S., Wollack, E., Wright, E.L.: Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological parameter results. The Astrophysical Journal Supplement Series 208 (2), 19 (2013) doi:10.1088/0067-0049/208/2/19
30. Unsöld, A., Baschek, B., The New Cosmos: An Introduction to Astronomy and Astrophysics. (2001)
31. Feynman, R.P., Morínigo, F.B., Wagner, W.G., Hatfield, B., Feynman Lectures On Gravitation. Addison-Wesley, Reading, Massachusetts (1995)
32. Lewis, G.N.: The conservation of photons. Nature 118 (2981), 874 (1926) doi:10.1038/118874a0
33. Kragh, H.: Photon: New light on an old name. arXiv.1401.0293, (2014)
34. Newton, I., Opticks: Or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light. William and John Innys, (1721)
35. Koskela, M., Annila, A.: Least-action perihelion precession. MNRAS 417 (3), 1742 (2011) doi:https://doi.org/10.1111/j.1365-2966.2011.19364.x
36. Riemann, B., Neue mathematische Prinzipien der Naturphilosophie. B. G. Teubner, (1892)
37. Yarkovsky, I.O., Hypothese Cinetique de la Gravitation Universelle et Connexion avec la Formation des Elements Chimiques. Moscow (1888)

38. Sandage, A.: The redshift-distance relation. IX. Perturbation of the very nearby velocity field by the mass of the Local Group. Astrophys. J. 307, 1 (1986) doi:10.1086/164387
39. Karachentsev, I.D., Kashibadze, O.G., Makarov, D.I., Tully, R.B.: The Hubble flow around the Local Group. MNRAS 393 (4), 1265 (2009) doi:10.1111/j.1365-2966.2008.14300.x
40. Annila, A.: Cosmic rays report from the structure of space. Advan. Astron. 135025, (11 pp) (2015) doi:https://doi.org/10.1155/2015/135025
41. Misner, C.W., Thorne, K.S., Wheeler, J.A., Gravitation. Freeman, (1973)
42. Lelli, F., McGaugh, S.S., Schombert, J.M., Pawlowski, M.S.: One law to rule them all: the radial acceleration relation of galaxies. Astrophys. J. 836 (2), 152 (23 pp) (2017) doi:10.3847/1538-4357/836/2/152
43. Annila, A.: Rotation of galaxies within gravity of the universe. Entropy 18 (5), 191 (2016)
44. Milgrom, M.: MOND vs. dark matter in light of historical parallels. Stud. Hist. Philos. Sci. Part B 71, 170 (2020) doi:https://doi.org/10.1016/j.shpsb.2020.02.004
45. Salucci, P.: Dark Matter in Galaxies: Evidences and Challenges. Found. Phys. 48 (10), 1517 (2018) doi:10.1007/s10701-018-0209-5
46. Annila, A.: Evolution of the universe by the principle of least action. Phys. Essays 30, 248 (2017) doi:0.4006/0836-1398-30.3.248
47. Castelvecchi, D.: The black-hole collision that reshaped physics. Nature 531, 428 (2016)
48. Einstein, A.: Uber den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes. Ann. Phys. 35 (10), 898 (1911)
49. Abbott, B.P., Abbott, R., Abbott, T.D., Abernathy, M.R., Acernese, F.: Observation of Gravitational Waves from a Binary Black Hole Merger. Phys. Rev. Lett. 116 (6), 061102 (2016) doi:10.1103/PhysRevLett.116.061102
50. Laughlin, R.B., A Different Universe: Reinventing Physics from the Bottom Down. Basic Books, (2005)
51. Feynman, R.P., Leighton, R.B., Sands, M., The Feynman Lectures on Physics, Vol. I: The New Millennium Edition: Mainly Mechanics, Radiation, and Heat. Basic Books, (2011)
52. Pawlowski, M.S., Famaey, B., Merritt, D., Kroupa, P.: On the persistence of two small-scale problems in ΛCDM. Astrophys. J. 815 (19), (12 pp) (2015) doi:10.1088/0004-637x/815/1/19
53. Hoffman, Y., Courtois, H.M., Tully, R.B.: Cosmic bulk flow and the local motion from Cosmicflows-2. MNRAS 449 (4), 4494 (2015) doi:10.1093/mnras/stv615
54. Annila, A., Salthe, S.: On intractable tracks. Phys. Essays 25 (2), 233 (2012) doi:10.4006/0836-1398-25.2.233
55. Annila, A.: Least-time paths of light. MNRAS 416 (4), 2944 (2011) doi:https://doi.org/10.1111/j.1365-2966.2011.19242.x
56. Annila, A.: Probing Mach's principle. MNRAS 423 (2), 1973 (2012) doi:https://doi.org/10.1111/j.1365-2966.2012.21022.x
57. Seife, C.: "Tired-Light" Hypothesis Gets Re-Tired. Science, (2001)
58. Landé, A.: The Case against Quantum Duality. Phil. Sci. 29 (1), 1 (1962) doi:10.1086/287837

59. Feynman, R.P., Leighton, R.B., Sands, M., The Feynman Lectures on Physics, Vol. III: The New Millennium Edition: Quantum Mechanics. Basic Books, (2011)
60. Couder, Y., Fort, E.: Single-Particle Diffraction and Interference at a Macroscopic Scale. Phys. Rev. Lett. 97 (15), 154101 (2006) doi:10.1103/PhysRevLett.97.154101
61. Andersen, A., Madsen, J., Reichelt, C., Rosenlund Ahl, S., Lautrup, B., Ellegaard, C., Levinsen, M.T., Bohr, T.: Double-slit experiment with single wave-driven particles and its relation to quantum mechanics. Phys. Rev. E 92 (1), 013006 (2015) doi:10.1103/PhysRevE.92.013006
62. Storey, P., Tan, S., Collett, M., Walls, D.: Path detection and the uncertainty principle. Nature 367 (6464), 626 (1994) doi:10.1038/367626a0
63. Afshar, S.S., In Proceedings of SPIE. The Nature of Light: What Is a Photon?, ed. by C. Roychoudhuri, Creath, K., (2005), p. 229–244
64. Afshar, S.S., Flores, E., McDonald, K.F., Knoesel, E.: Paradox in Wave-Particle Duality. Found. Phys. 37 (2), 295 (2007) doi:10.1007/s10701-006-9102-8
65. Knight, A.: No Paradox in Wave–Particle Duality. Found. Phys. 50 (11), 1723 (2020) doi:10.1007/s10701-020-00379-9
66. Davidović, M., Sanz, A.S., Arsenović, D., Božić, M., Miret-Artés, S.: Electromagnetic energy flow lines as possible paths of photons. Phys. Scr. T135, 014009 (2009) doi:10.1088/0031-8949/2009/t135/014009
67. Batelaan, H., Tonomura, A.: The Aharonov–Bohm effects: Variations on a subtle theme. Phys. Today 62 (9), 38 (2009) doi:10.1063/1.3226854
68. Aharonov, Y., Bohm, D.: Significance of Electromagnetic Potentials in the Quantum Theory. Phys. Rev. 115 (3), 485 (1959) doi:10.1103/PhysRev.115.485
69. Fang, K., Yu, Z., Fan, S.: Experimental demonstration of a photonic Aharonov-Bohm effect at radio frequencies. Phys. Rev. B 87 (6), 060301 (2013) doi:10.1103/PhysRevB.87.060301
70. Bokulich, P.: Complementarity, wave-particle duality, and domains of applicability. Stud. Hist. Philos. Sci. Part B 59, 136 (2017) doi:https://doi.org/10.1016/j.shpsb.2017.06.004
71. Griffiths, D., Introduction to Elementary Particles. 2 edn. Wiley-VCH, (2008)
72. Wheeler, J.A., In Quantum Theory and Measurement, ed. by J.A. Wheeler, W.H. Zurek Princeton University Press Princeton (1984)
73. Marlow, A.R., Mathematical Foundations of Quantum Theory. Academic Press, (1978)
74. Jacques, V., Wu, E., Grosshans, F., Treussart, F., Grangier, P., Aspect, A., Roch, J.-F.: Experimental realization of Wheeler's delayed-choice Gedanken experiment. Science 315 (5814), 966 (2007) doi:10.1126/science.1136303
75. Egg, M.: Delayed-Choice Experiments and the Metaphysics of Entanglement. Found. Phys. 43 (9), 1124 (2013) doi:10.1007/s10701-013-9734-4
76. Keller, O.: On the theory of spatial localization of photons. Phys. Rep. 411 (1), 1 (2005) doi:https://doi.org/10.1016/j.physrep.2005.01.002
77. Božić, M., Vušković, L., Davidović, M., Sanz, Á.S.: On Wheeler's delayed-choice Gedankenexperiment and its laboratory realization. Phys. Scr. T143, 014007 (2011) doi:10.1088/0031-8949/2011/t143/014007
78. Heisenberg, W., Physics and Philosophy: The Revolution in Modern Science. Allen & Unwin, London (1958)

79. Seager, W.: A Note on the 'Quantum Eraser'. Phil. Sci. 63 (1), 81 (1996) doi:10.1086/289895
80. Lévy-Leblond, J.-M.: On the Nature of Quantons. Sc&Ed 12 (5), 495 (2003) doi:10.1023/A:1025382113814
81. Hong, C.K., Ou, Z.Y., Mandel, L.: Measurement of subpicosecond time intervals between two photons by interference. Phys. Rev. Lett. 59 (18), 2044 (1987) doi:10.1103/PhysRevLett.59.2044
82. Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. Lett. 47, 777 (1935) doi:10.1103/PhysRev.47.777
83. Kocher, C.A., Commins, E.D.: Polarization Correlation of Photons Emitted in an Atomic Cascade. Phys. Rev. Lett. 18 (15), 575 (1967) doi:10.1103/PhysRevLett.18.575
84. Freedman, S.J., Clauser, J.F.: Experimental Test of Local Hidden-Variable Theories. Phys. Rev. Lett. 28 (14), 938 (1972) doi:10.1103/PhysRevLett.28.938
85. Aspect, A., Grangier, P., Roger, G.: Experimental realization of Einstein-Podolsky-Rosen-Bohm gedanken experiment: a new violation of Bell's Inequalities. Phys. Rev. Lett. 49 (2), 91 (1982) doi:10.1103/PhysRevLett.49.91
86. Smerlak, M., Rovelli, C.: Relational EPR. Found. Phys. 37 (3), 427 (2007) doi:10.1007/s10701-007-9105-0
87. Barut, A.O., Meystre, P.: A classical model of EPR experiment with quantum mechanical correlations and bell inequalities. Phys. Lett. A 105 (9), 458 (1984) doi:https://doi.org/10.1016/0375-9601(84)91036-3
88. Krechmer, K.: Measurement unification. Measurement 182, 109625 (2021) doi:https://doi.org/10.1016/j.measurement.2021.109625
89. Megidish, E., Halevy, A., Shacham, T., Dvir, T., Dovrat, L., Eisenberg, H.S.: Entanglement Swapping between Photons that have Never Coexisted. Phys. Rev. Lett. 110 (21), 210403 (2013) doi:10.1103/PhysRevLett.110.210403
90. Hess, K., Philipp, W.: A possible loophole in the theorem of Bell. 98 (25), 14224 (2001) doi:10.1073/pnas.251524998 %J Proceedings of the National Academy of Sciences
91. Hess, K., Philipp, W.: Breakdown of Bell's theorem for certain objective local parameter spaces. 101 (7), 1799 (2004) doi:10.1073/pnas.0307479100 %J Proceedings of the National Academy of Sciences
92. Chen, G.: Collapse of Bell's Theorem. Journal of Modern Physics 10, 1157 (2019) doi:10.4236/jmp.2019.1010076
93. Muchowski, E.: On a contextual model refuting Bell's theorem. EPL (Europhysics Letters) 134 (1), 10004 (2021) doi:10.1209/0295-5075/134/10004
94. Kotler, S., Peterson, G.A., Shojaee, E., Lecocq, F., Cicak, K., Kwiatkowski, A., Geller, S., Glancy, S., Knill, E., Simmonds, R.W., Aumentado, J., Teufel, J.D.: Direct observation of deterministic macroscopic entanglement. Science 372 (6542), 622 (2021) doi:10.1126/science.abf2998
95. Mercier de Lépinay, L., Ockeloen-Korppi, C.F., Woolley, M.J., Sillanpää, M.A.: Quantum mechanics–free subsystem with mechanical oscillators. Science 372 (6542), 625 (2021) doi:10.1126/science.abf5389
96. Cavanagh, J., Fairbrother, W.J., Palmer, A.G., Skelton, N.J., Protein NMR Spectroscopy: Principles and Practice. Elsevier Science, (1995)

97. Annila, A.: The Matter of Time. Entropy 23 (8), 943 (2021) doi:10.3390/e23080943
98. Emery, N., Markosian, N., Sullivan, M., In The Stanford Encyclopedia of Philosophy, ed. by E.N. Zalta Metaphysics Research Lab, Stanford University (2020)
99. Clauset, A., Shalizi, C.R., Newman, M.E.J.: Power-law distributions in empirical data. SIAM Rev. 51 (4), 661 (2009) doi:https://doi.org/10.1137/070710111
100. Maupertuis, P.-L.M.d.: Les loix du mouvement et du repos déduites d'un principe métaphysique. Histoire de l'Académie Royale des Sciences et des Belles Lettres, 267 (1746)
101. Terrall, M., The Man Who Flattened the Earth: Maupertuis and the Sciences in the Enlightenment. University of Chicago Press, Chicago (2002)
102. Merritt, D.: Cosmology and convention. Stud. Hist. Philos. Sci. Part B 57, 41 (2017) doi:10.1016/j.shpsb.2016.12.002
103. Smeenk, C.: Some reflections on the structure of cosmological knowledge. Stud. Hist. Philos. Sci. Part B 71, 220 (2020) doi:https://doi.org/10.1016/j.shpsb.2020.05.004
104. Fleck, L., Genesis and Development of a Scientific Fact. University of Chicago Press, Chicago (1981)
105. Barrett, Jeffrey A.: Are Our Best Physical Theories (Probably and/or Approximately) True? Phil. Sci. 70 (5), 1206 (2003) doi:10.1086/377401
106. Vaihinger, H., The Philosophy of "As If". Kegan Paul., London (1923)
107. Fine, A.: Fictionalism. Midwest. Stud. Phil. 18 (1), 1 (1993) doi:https://doi.org/10.1111/j.1475-4975.1993.tb00254.x
108. López-Corredoira, M.: Non-standard models and the sociology of cosmology. Stud. Hist. Philos. Sci. Part B 46, 86 (2014) doi:https://doi.org/10.1016/j.shpsb.2013.11.005
109. Vanderburgh, W.L.: The Dark Matter Double Bind: Astrophysical Aspects of the Evidential Warrant for General Relativity. Phil. Sci. 70 (4), 812 (2003) doi:10.1086/378866
110. Kuhn, T.S., The Essential Tension: Selected Studies in Scientific Tradition and Change. Chicago University Press, Chicago, IL (1977)