

# Tangled in entanglements

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**Abstract.** Conceptual conundrums of quantum mechanics known as instantaneous action-at-a-distance and inseparable wave-particle character are examined by the principle of least action. When a measurement is understood as a natural process of energy transfer, it follows that the spin of a particle just as the polarization of a photon will remain indetermined for the observer until at least one quantum of action is received from the object. Thus it is the dissipative detection that places the photon polarization in the observer's frame of reference. This frame will instantaneously apply also to the polarization of the other photon that emerged from the same radiative decay, provided that the correlation between the two photons has not been perturbed ever since. The wave-particle duality demonstrated by the double-slit experiment can also be understood when a single photon or a single electron is recognized as a flow of energy from a source to a detector. This flow will invariably perturb surrounding energy density, at least the vacuum density. Hence the energy density in motion, comprising the particle and perturbations in the surrounding, channels via two or more paths, the flows through the slits depend on each other. This will manifest as the inseparable particle-wave character.

**Keywords:** action-at-a-distance; double slit experiment; evolution; quantum paradoxes; the principle of least action

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## 1. Introduction

Spooky action-at-a-distance is one of the weirdest quandaries of quantum mechanics. The phenomenon has been chewed up so thoroughly that it perhaps shows a bad taste even to attempt to take a bite of it – or eventually a complete ignorance on the nature of the body in question. To have a new look of the correlation without a force carrier, let us imagine how the puzzling phenomenon [1,2,3] would appear to a rookie knowing only basic physics. He would specifically like to understand, why the measurement of a photon's polarization will instantaneously reveal also the polarization of its mate photon that has emerged from the same radiative decay.

At first it may appear unproductive to abandon the well-established formalism of quantum mechanics, but that theory is limited to describe conserved systems just as statistical mechanics is limited to account for closed systems [4]. Since probabilities are forced to sum up to unity, the quantum theory, just as classical statistical mechanics, fails to account for detection where at least one quantum is either acquired from an object system to an observer or *vice versa*. In contrast to the conserved formalism, the universal law of maximal dispersal of energy, known as the principle of least action in its original form á la Maupertuis [5], identifies energy differences between the system and its surrounding as the motive that will force flows of quanta from the system to its surroundings (or *vice versa*). This universal principle to consume free energy in least time is familiar to a rookie. In the same way heat flows from hot to cold.

The simple imperative provides a fresh look into a seemingly complicated problem. The natural principle has been recently derived as an equation of motion from statistical physics of open systems [6,7] and applied in analyses of diverse problems [8,9]. At first the physical portrayal may appear to some too concrete and simple because customarily much of quantum mechanics is communicated using abstract concepts and illustrated by gedanken experiments. Here we deliberately limit to plain observations communicated using basic concepts. Conversely we will avoid thought experiments and concepts whose correspondence to reality is unclear to a rookie. By this strictly naturalistic description we hope also to avoid entering philosophical discussions to which the conundrums of quantum mechanics have given rise over the years.

## 2. Phases exist relative to references

An observation, when described as a natural process [10], requires some flow of quanta between an observer and an object [6]. Thus the observer must capture at least one quantum of action, i.e., one photon, from the object. Alternatively the observer may perceive the object by contributing at least one photon to it. Thus our Rookie reasons that the measurement is an energy transduction process that will move the object from an initial state either to a final state that is down in energy or to another final state that is up in energy relative to the initial state – which one of the available alternatives depends on whether the observer is in the absorptive or emissive phase relative to the object. For example, when the observing detector is at a ground state, it may accept photon from the object provided that the object is at an excited state to donate the photon. Conversely when the observing detector is at an excited state, it may emit photon to the object provided that the object is at the ground state to absorb the photon. When both the observer and the object are at the ground state or both are at the excited state, there cannot be any flow of quanta hence nothing can be detected.

Notably, since Rookie regards the measurement as an energy transduction process, he finds no need for the prevailing presumption that the unperturbed object would be in some superposition of states. Therefore he deduces that the indeterminacy in the outcome of a measurement is not contained in the initial state of the object as such, but follows from randomness in the phase between the object and observer. When the phase between the object's and observer's frames is arbitrary, the flow of energy will direct randomly along a path among the alternative absorptive and emissive transitions. Thus the observation, when uncorrelated with object's motions, will bring the object system at random from the initial state to a final state. Thus a series of uncorrelated measurements will deliver a distribution of outcomes. Conversely, when the phase between the object's and observer's frames is not arbitrary, the correlated phenomena will appear.

When the measurement is understood as an energy transduction process, it follows that the polarization of a photon will be established relative to the frame of observation (figure 1). In other words the spin of a force carrier remains indetermined, as stated by the Einstein–Podolsky–Rosen (EPR) paradox, until the detection relates it to the observer's frame. Likewise for a correlated pair of two photons, the indeterminacy of polarization with respect to the observer will prevail, but the particular polarization of one photon relative to the other photon will survive as long as the observation or any other process will perturb neither one of the two photons that resulted from the same decay. In the absence of forces the initial phase ( $\varphi = \pi$ ) between the two photons will remain invariant, i.e., at a constant value in accordance with the Newton's law of constant motion ( $d_t\varphi = 0$ ).

The entanglement, i.e., the correlation between the two particles is fragile. When the two particles experience unequal energy density gradients, the degree of order will invariably decrease because the ensuing flows of energy differ for the two particles in propagation. In view of that, to preserve the crucial correlation, i.e., to retain the relative phase between the pair of particles does not require the presence of a force carrier whose coupling in fact would destroy the correlation. When one of the two correlated photons having opposite polarizations is related to the observer's frame in the detection, the same frame, irrespective of the outcome, will apply instantaneously to the other photon having the opposite polarization – provided that the mate has not been perturbed in the mean time by any other process. The idea in knowing instantaneously one from the other is the same when one marble out of two having opposite colors is drawn from a sealed bag for inspection of its color.

Irrespective of the outcome the color of the other marble having the opposite color is known instantaneously – provided that the mate has not been changed in the mean time by anyone. To deduce the color of one from the other does not depend on particular colors, only that they are opposite for the two marbles. Likewise, to deduce the polarization of one photon from the other does not depend on particular polarizations, only that they are opposite for the two photons which they have to be in order to conserve the angular momentum in the decay that produced the two quanta.

Thus Rookie concludes that indeed no flow of energy, i.e., a causal connection, is required to deduce instantaneously the spin of the other particle from the one referenced at the measured site provided that their mutual orientation has remained the same ever since the two emerged as a correlated pair [11]. However to ensure that the detected photons in fact were a correlated pair, communication from one site of a recording to the other site of detection is needed. The mandatory message can at best flow at the speed of light since any information must have some form of physical representation [12,13]. Hence Rookie reasons a flow of information is the flow of energy which will change the receiver state from that where recordings of a photon polarization are random to that where correlations are recognized on the basis of the information given about the mate photon. Likewise, it does not mean much to pick a series of marbles of red, blue and white from a bag until one is told that another series of green, yellow and black marbles, the sequence of opposite color, were also drawn from the same bag.



Figure 1. A decay process (at the center) outputs two photons (blue and red) which propagate in the opposite directions. As long as neither one of the two is subject to unequal forces, the polarization of one photon will remain intact relative to its mate but indetermined relative to any external frame of reference (an axis system in blue). The detection will place the polarization of one photon in the reference frame relative to the observer and the same frame will apply instantaneously also to the other photon provided that the correlated pair has remained unperturbed ever since it emerged from the decay.

The resolution of the EPR paradox as given above does not involve hidden variables, merely concepts of energy and time that together define an action  $S = \int \mathbf{p} \cdot d\mathbf{x}$  which integrates momenta  $\mathbf{p}$  along paths  $d\mathbf{x} = \mathbf{v} dt$  where the kinetic energy  $2K = p v$  landscape is in motion with velocity  $\mathbf{v}$  during time  $dt$  [5,6,7]. An observation, just any other flow of energy, will drive the energy landscape in evolution from a stationary state toward another [6,7] by consuming at least the quantum of action, corresponding to the Planck's constant  $h$  (figure 1). The indeterminacy  $\Delta 2K \Delta t \geq h$  is inherent in the detection because no state can be determined without causing a change of the state at least by  $h$ . A macroscopic system does not mind much of losing few quanta but a microscopic system will suffer severely, eventually going extinct when losing the very last quantum of action to the observing surroundings. This impact of detection on the object has been phrased memorably by Pascual Jordan *Observations not only disturb what is to be measured, they produce it ...* [14].

### 3. Inseparable forces and flows

Let us dissect another central subject of quantum quandaries, the double-slit experiment. Our Rookie would specifically like to understand, why the wave and particle natures of light and other forms of energy densities cannot be separated from each other.

Knowing that according to the principle of least action flows of energy will direct to diminish energy density differences in least time, it follows that the flows of energy, such as a stream of photons or electrons from a high density source, will disperse along the paths of least action, for example, those passing via two slits. The flows

of energy over a time interval  $t$  will consume the driving forces due to the scalar  $U$  and vector  $Q$  potential differences, and the balance is maintained by a change in the kinetic energy  $2K$ . The conservation among the three forms of actions  $2Kt = -Ut + Qt$  was conjectured a long time ago [15,16]. The balance equation is easy to recall in a differential form where an electron is falling down along electric field and dissipating energy to the surroundings as light down along vector potential gradient orthogonal to the electron's directed path [6,17]. Curiously though, when energy disperses from a source down along two or more paths, the natural process of breaking one stationary-state symmetry for another will be intractable. In other words the path-dependent process cannot be integrated to a closed form. The derivatives at the branching points are inexact, i.e., the tangent is ill-defined at a fork of path since the quantum is indivisible. The flows that consume the same source of energy are interdependent since a flow by the mere act of flowing will decrease the driving density difference and when the same gradient fuels also other flows, these will be affected as well and *vice versa* [18]. In general, natural systems when changing state are non-Hamiltonian. Only when a single path is provided, forces and flows can be separated from each other to allow integration to a closed form. Also at the stationary state trajectories are deterministic since energy of the system is invariant.

The progress of a natural process, where quantized flows of energy are leveling off the density difference, is measured by a change  $d_t P = d_t \int \psi^* \psi d\mathbf{x}$  in the probability  $P$ . So the probability is physical. It is a measure of the system's status in energetic terms. The wave function  $\psi(\mathbf{x},t)$  is often regarded merely as abstraction, but here it turns out to be a particularly fitting physical formalism, via its mutually orthogonal spatial and temporal variables, to describe a flow of energy density from one locus of energy density along  $\mathbf{x}$  to another locus during time  $t$ . When the flows level off the density differences, the wave functions will change. Eventually the natural process will attain the state where all forces are in perfectly balanced. In other words at the free-energy minimum state the energy landscape has no curvature [6]. Then the system has arrived at a thermodynamic steady state  $d_t P = 0$  where the opposite circulations of energy densities  $\psi$  and  $\psi^*$ , as familiar from Kirchhoff's law, are equally abundant on their common trajectory. The conserved quantities of the stationary state, most notably mass, relate to the symmetry group of the circuit via Noether's theorem [19]. Since energy of the stationary state is conserved there is a norm and hence a unitary transformation can be found that will remove the time-dependence altogether. Thus dynamics of a Hamiltonian system is completely reversible whereas the consumption of free energy results in an irreversible process.

It does not occur to Rookie that some form of an energy density could possibly be a point-like singularity that would fit in to its surrounding energy densities without causing any perturbation. On the contrary, a photon has its wavelength and also the electron's finite magnetic moment and charge imply some finite-sized of a circulation whose energy density will invariably perturb surrounding energy densities [7]. This of course manifests itself, e.g., as an electric field. Since no space is without some energy density [8,9], at least the vacuum density will be perturbed by the flows of densities, for example in the form of light or electrons that propagate down along the available paths from a source to the sink that acts as a detector. The non-zero values of permittivity and permeability that define the speed of light  $\epsilon_0 \mu_0 = c^{-2}$  and impedance  $\epsilon_0 / \mu_0 = Z^2$  reveal that the all-around present vacuum density is not zero. The finite universal energy density manifests itself in Casimir effect [20] and Aharonov-Bohm experiment [21]. In particular the dynamic Casimir effect reveals that the vacuum density comprises photons [22]. When an electron propagates through an energy density  $U$  that is applied on the top of the vacuum density, the interference pattern will acquire an additional shift  $\Delta\phi = Ut/\hbar$  in the phase, known as the Berry phase [6,23]. Conversely, it follows that if the vacuum density were zero, there would be no interference pattern without applied potential. Thus Rookie understands that as long as the two slits are within the spread of an energy density perturbation, the flow of energy density through one slit will depend on the flow through the other slit because both streams consume the common density difference. When one slit is conducting, the density difference across the other slit will also change and affect the other flow, and *vice versa* (figure 2). Therefore inseparable interference effects will arise, when the coherent flows recombine after they have taken two or more paths to maximize the overall dispersal of energy in the least time [24]. Moreover, any attempt to sniff, how the flows of energy density distribute between to the two slits, will require, just as any

measurement, some flow of energy between the object and its observer, which in turn will obscure the interference pattern when contributing incoherently to the energy dispersal process.



Figure 2. Photons (or electrons) are energy densities (depicted as contrast variations in the surrounding density) that propagate via two available paths (openings in the red wall) down along the energy density gradient between a source (up) and a sink (down). A propagating energy density will perturb the surrounding vacuum energy density and thereby also induce energy density differences that in turn act as driving forces. When the density perturbation extends from one slit over to the other, the two flows, that are consuming it, will depend on each other. Since the flow of energy density through one slit will affect the density difference across the other slit, the paths are interdependent and give rise to inseparable particle-wave character. (<http://www.falstad.com/ripple/>)

The interdependence between the flows of energy densities and the energy density differences as their driving forces is familiar also from the three-body problem [25] and from the traveling salesman problem [26]. When there are three or more degrees of freedom, irreversible processes are intractable because the forces and flows cannot be separated from each other for the integration to a closed form [27]. Only when a single path is provided, i.e., when there are only two degrees of freedom, will the energy dispersal process be deterministic. Physics mostly focuses upon these special cases of bound actions known as the Hamiltonian systems where the forces can be separated from the flows and the motions can be tracked by integration.

#### 4. Actions constitute space and time

Undoubtedly there are many more challenging questions to inspect, for example quantum Zeno effects [28,29] where flows of energy in detection correlate with the changes of state of the object's with (periodic) energy density variations of the observer. However, we have seen enough to know the way of applying the universal law of least-time free energy consumption. Reality is seen in a holistic way so that diverse systems take part in the overall process of energy dispersal by interacting with their surrounding systems [30]. In other words no system is without some surroundings, at least that of the universal surroundings known as the vacuum. Therefore everything depends on everything else, in concert with Mach's principle. It is the energy differences between the system and its surroundings that will drive changes of state of both the system and its surrounding system. When the system evolves from one state to another, the boundary conditions defined by the surroundings will change too because it is the surroundings that will either supply or draw the system's change in energy.

Physics like any other discipline is beguiled by ambiguity in its most central concepts, most notably space and time. Commonly these are used as axioms, but of course do deserve physical presentations to be solid cornerstones of our description of reality. According to the principle of least action an element of space is a closed stationary action composed of one or multiples  $\hbar$  [7]. This spatially localized energy density is surrounded by other actions. Their mutual energy density differences are the driving forces that will diminish with time whose flow, in turn, is a flow of energy density. An element of time is an open action composed of one or multiples  $h$ . The open actions carry energy from high-density closed confinements to others of lower densities. These natural processes, even when the equation of motion is intractable, will naturally select from the available variation the least-time paths of dispersal, known also as geodesics [9,31,32]. Our Rookie, when facing the diversity of natural phenomena, is easily lost in case-by-case reasoning garnished with different formulas, but

prefers to apply the general principle of least action that may be too transparent to catch eyes of those tangled in entanglements.

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