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Wave Particle Duality: De Broglie Waves in Indirect Quantum Measurements

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Abstract

The wave particle duality is one of the less intuitive properties of Quantum Mechanics. Under some particular experimental circumstances, when corpuscular systems can follow two alternative paths which later on rejoin and superpose, some wave like interference happens. If one of the paths is blocked the wave like behaviour disappears. As the particle arrives to the final position we can infer it has followed the free path, and therefore it is always spatially separated of the blocking system and there is not local interaction between them. The simplest hypothesis is that a third element, a physical wave, allows an indirect interaction between particle and blocking system, a de Broglie wave. A simple mathematical model, extension of General Relativity, shows how this indirect interaction can happen, mediated by gravity.

Subject Areas

Quantum Mechanics

Keywords

Wave Particle Duality, De Broglie Waves, Dark Energy, Dark Matter

1. Introduction

The wave particle duality is perhaps the most astonishing property of microscopic systems, elementary particles, atoms, molecules, … In some experimental circumstances, when the spatially localised microscopic system can follow two or more trajectories which later on rejoin, it is observed a typical wave behaviour of superposition and interference. In Quantum Mechanics, the description of this phenomenon is that the amplitudes of probability (complex numbers) associated to different trajectories are added in the joining point and, as complex numbers, they have both modulus and phase, so that relative phases between different components give account of a wave like superposition and interference, sometimes the total amplitude increases and others it diminishes. This astounding phenomenon has generated different interpretations. Sometimes it is said that a microscopic system is neither a particle (corpuscular, spatially localised system) nor a wave (spatially distributed), but something different, a quantum entity. However, there is not a sharp limit between microscopic and macroscopic systems; in fact, experimental improvements have shown this wave like phenomenon in larger and larger molecules. We should consider the properties of macroscopic systems as statistical averages of a huge number of microscopic components. Some people consider an extremely strange rigorous approach and understand that we do not have an experimental evidence of unobserved phenomena (we do not know if the moon is there when we do not look), which is a tautology. In this line, we can only corroborate the spatially localised property of particles and molecules when they are observed (a dot in a screen, a line in a cloud chamber), and we really do not know what is its character when not observed. It is obvious that an observation, a measurement, means some interaction with the measurement apparatus, so that the physical state of the observed entity must change along the measurement process. But this is not the same as saying that the character of this entity changes, e.g. from wave like to particle like entity. Ockam's razor should be applied, particles are also localised systems in space when not observed. It is much simpler the hypothesis that accompanying particles and other microscopic systems there is a wave, a spatially distributed system which interacts with the particles and exerts some influence in their trajectory, giving account of the wave like behaviour. Even before the formulation of Quantum Mechanics, de Broglie [1] [2] proposed to associate a wave to a particle of momentum p through the relation $p\lambda = h$, where λ is the wave length and h is Planck's constant.

In this article it is presented a careful physical analysis of some experiments in which the wave behaviour appears, and it is concluded that there could be an additional distributed system, a wave, accompanying particles and other microscopic systems. The reasoning is based in the relativistic rule that all physical interactions must be local. Obviously, if this wave exists the wave particle duality becomes something understandable, more intuitive. Next section is devoted to describe three experiments where the wavelike behaviour appears, one of them the well known two slit experiment, in which we need a statistical sample (repetition of the experiment) to observe the diffraction pattern or its absence. I have chosen the other two experiments because the change of final state of the particle, when the superposition is suppressed, can be checked in a single run of the experiment. A physical analysis follows, and the argument is decomposed into elementary steps to facilitate the reasoning.

The physical analysis of these experiments does not give any clue about the way in which particles and wave interact. Therefore, any proposal at this stage, in absence of experimental data, is highly speculative. The simplest extension of General Relativity is the so called Einstein constant, associated to the vacuum energy density; it is a possible explanation of dark energy. The second simplest extension is to consider a scalar dynamical field obeying a harmonic oscillator variational principle. I develop this mathematical model in the last section, and it describes an indirect interaction between the hypothetical wave and matter, mediated by gravity. It is interesting to notice that such a simple system generates both positive and negative terms in the scalar curvature of the metric of space time.

2. Experimental Facts

In this section some experiments where the wave particle duality is illustrated are reviewed. In the first two cases the particle can follow two alternative paths which later on rejoin. In the formalism of Quantum Mechanics the two amplitudes of probability superpose and some interference happens. Because of the destructive interference in one of the two exit gates the particle is always detected at the other gate, 100% of the times. In the second part of the experiments one of the alternative paths is blocked (for example, with a particle detector). As far as there is no more superposition and interference we can sometimes detect the particle in the previously forbidden exit gate. This can be understood as an indirect measurement of position; when the blocking system does not detect the particle, which is found at the final position, we can infer it has followed the alternative free path.

2.1. Mach-Zehnder Interferometer

In the first experiment we consider a Mach-Zhender interferometer [3] [4], two beam splitters and two mirrors in a square configuration. In its most common form, a cube, a beam splitter is made from two triangular glass prisms which are glued together at their base using polyester, epoxy, … The thickness of the resin layer is adjusted such that (for a certain wavelength) half of the light incident through one "port" (*i.e.*, face of the cube) is reflected and the other half is transmitted without deviation. Photons, one at a time, are injected through the first beam splitter. The photon can follow either arm of the interferometer and reaches the last beam splitter. We can adjust the length of the arms of the interferometer in such a way that all photons are detected at exit gate A. In the physical interpretation, each arm of the interferometer has associated an amplitude of probability. In the last beam splitter both amplitudes superpose and interfere, giving way to a wave like phenomenon. The adjustment of the lengths of the arms generates a totally destructive interference at exit gate B, so that all photons are detected at A (**Figure 1**).

In the second part of the experiment we introduce a new element, a system blocking one of the arms of the interferometer. It could be a photodetector. Now, the photon can be detected at the blocking system fifty per cent of the times and it can arrive to the final beam splitter another fifty per cent. There, the beam splitter breaks the trajectory and we can find the photon at exit gates A or B with even probability (**Figure 2**). In the quantum formalism, the blocking system blocks one of the amplitudes of probability, so that there is no more superposition and interference at the last beam splitter. We are interested in particular in the last possibility, the photon found at gate B. There is an explicit change of final state of the particle, change of final position.

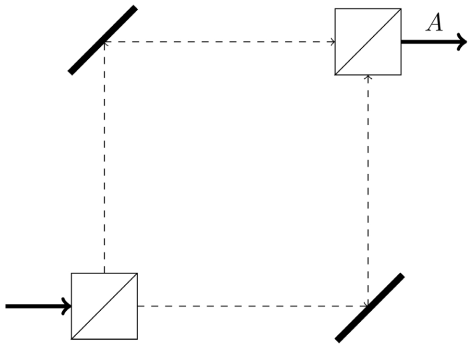

Figure 1. Mach-Zehnder interferometer.

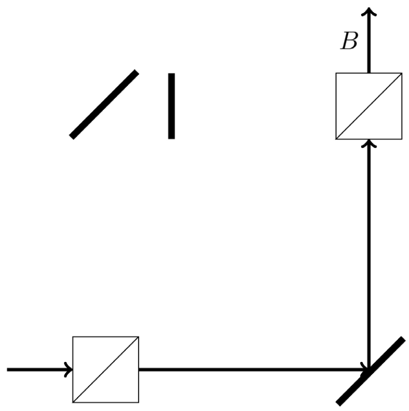

Figure 2. Mach-Zehnder interferometer with blocking system.

2.2. Train of Stern-Gerlach Devices

In this experiment we arrange a train of Stern-Gerlach devices [5]. In quantum physics, the Stern-Gerlach experiment demonstrated that the spatial orientation of angular momentum is quantized. Thus, an atomic scale system is shown to have intrinsically quantum properties. In the original experiment, silver atoms were sent through a spatially varying magnetic field, which deflected them before they struck a detector screen, such as a glass slide. Particles with non-zero magnetic moment were deflected, owing to the magnetic field gradient, from a straight path. The screen revealed discrete points of accumulation, rather than a continuous distribution, owing to their quantized spin. In the experiment we consider electrons are used, previously selected with X up spin, which are sent through the experimental set up. The quantized spin of electrons is $\pm\frac{1}{2}\hbar$. The fist device, with Y spatial orientation, splits the trajectory of the electron into two possible paths, Y up and Y down spin. Using an adequate electromagnetic field we can drive both trajectories into a new device with $-Y$ orientation and opposite placement. There, both trajectories superpose. A final device with X orientation determines the final spin state of the electron. If everything is well adjusted all electrons are detected at exit gate A, X up spin. The quantum interpretation is that both Y up and down spin trajectories superpose and interfere, reconstructing the original X up spin state. Again, it is a wave like phenomenon (**Figure 3**).

In the second part of the experiment we introduce a blocking system in the intermediate Y down spin trajectory (see **Figure 4**). Now, if the electron arrives to the final Stern-Gerlach device (obviously with Y up spin) there is no more superposition and interference, and it can be detected at either gates A o B. We are interested in the last case, electron detected at gate B, showing an explicit change of state, final position of the electron.

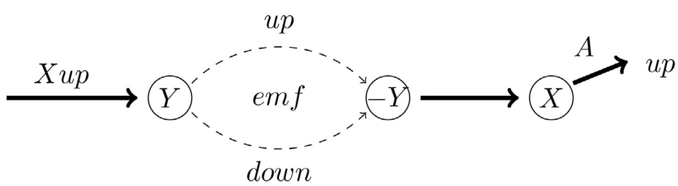

Figure 3. Train of Stern-Gerlach devices.

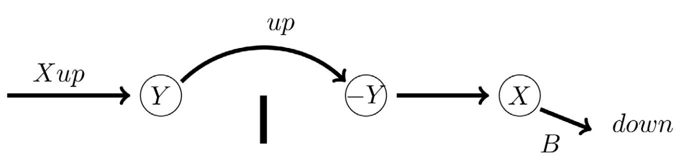

Figure 4. Train of Stern-Gerlach devices with blocking system.

2.3. Two Slit Experiment

In the two slit experiment there is a source of electrons with fixed velocity. The electrons are directed towards a first screen with two parallel slits. Some electrons go through the slits and arrive to a final screen where they are detected as dots. The distance between the slits is chosen (according to the velocity of the electrons) to enhance the visibility of the interference pattern, which appears because of the wavelike behaviour of electrons. After enough repetitions of the experiment (a statistical sample) there appear some bands with maximal density of dots and others with minimal density, in a typical interference pattern. In the quantum description we associate an amplitude of probability to each slit, and its superposition at the final screen gives way to the interference pattern. Particles (spatially localised systems) behave as waves.

If now one of the slits is blocked, only electrons following the open slit arrive to the final screen (indirect measurement of position). In the quantum description there is only one source of amplitude of probability, the open slit, and there is no more superposition and interference. We observe (using a statistical sample) a normal diffusion pattern, with a central area with high density of dots and lower densities when the distance to the center increases. The interference pattern does not appear.

3. Physical Analysis: Interactions

A physical analysis of the first two experiments is developed in the following.

1) In the first part of the experiments the particle (photon or electron) enters the experimental set up, and after a chain of interactions (with beam splitters and mirrors, or with Stern-Gerlach devices and the electromagnetic field) arrives to a final state (final position at gate A) where it is detected.

2) In the second part of both experiments the final state (final position) of the particle is different in the case of interest; the particle is detected at gate B. We can infer that it has followed a different chain of interactions, that is, at least one interaction must have been different.

3) The origin of this new interaction(s) must necessarily be the unique additional element in the experimental set up, the blocking system. The only way a system can exert some influence in a process is through interaction.

4) We can also infer the trajectory of the particle in the second part of the experiments (see the figures). The particle can arrive to exit gate B only if it follows the unblocked path, arm of the interferometer or spin path. There is a spatial separation between the system blocking one path and the particle at the other path.

5) We must conclude that particle and blocking system do not have a local interaction, they are spatially separated in the case of interest. Some other (new) system must play the role of intermediate element allowing an indirect interaction between particle and blocking system.

6) The simplest hypothesis is that a wave follows both paths of the experiments, and that the corresponding wave component is blocked in the second part of the experiments by the additional blocking system. In the first part, when both components of the wave arrive to the final position, there is superposition and interference, giving way to exit of the particle through gate A, because there is destructive interference at gate B. We must understand that there is some correlation between amplitude of the wave and probability of finding the particle. In the second part of the experiments one of the components of the wave is blocked and there is no more superposition and interference, so that particles arriving to the final position (beam splitter or Stern-Gerlach device) follow exit gate B fifty percent of the times.

We could denote de Broglie waves to this new distributed system. In the two slit experiment we get an interference pattern in the final screen when both slits are open, while the pattern disappears when one slit is blocked. When the electron arrives to the final screen in this last configuration we can infer it has gone through the open slit, and therefore it has not had local interaction with the blocking system (spatial separation). Again we need an additional system to intermediate in the interaction. That is, the de Broglie wave length associated to elementary particles and other microscopic systems is the wave length of a real, physical wave accompanying the spatially localised particle.

4. A Mathematical Model

The simplest extension of General Relativity is to add a cosmological constant, which could be related to the energy density of vacuum. The second simplest extension is to consider a scalar field obeying a harmonic oscillator variational principle. This scalar field could be identified with the de Broglie wave. The corresponding action is added to the Einstein-Hilbert action of General Relativity to get (with signature $(-+++)$)

$$2\kappa\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}R - \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(g^{\mu\nu}\partial_\mu\Lambda\partial_\nu\Lambda + \frac{\lambda^2}{l_P^2}\Lambda^2\right) + 2\kappa\mathcal{S}_{mr} \tag{1}$$

where R is the scalar curvature of the metric of space-time, Λ is the scalar field, l_P is Planck's length, λ^2 is an adimensional positive coupling constant, $\kappa = \frac{8\pi G}{c^4}$ and $\mathcal{S}_{mr}$ is the action of normal matter (and radiation). Notice that Planck's constant $\hbar$ is incorporated into the action through l_P, so that the proposed model represents a semiclassical quantum correction to General Relativity.

Applying the variational calculus formalism [6] we get the modified general relativistic equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa T_{\mu\nu} + \frac{1}{2}\partial_\mu\Lambda\partial_\nu\Lambda - \frac{1}{4}g_{\mu\nu}g^{\alpha\beta}\partial_\alpha\Lambda\partial_\beta\Lambda - \frac{1}{4}g_{\mu\nu}\frac{\lambda^2}{l_P^2}\Lambda^2 \tag{2}$$

and the accompanying wave equation

$$g^{\mu\nu}\partial^2_{\mu\nu}\Lambda + \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\right)\partial_\nu\Lambda - \frac{\lambda^2}{l_P^2}\Lambda = 0 \tag{3}$$

These coupled equations give account of the indirect interaction between particles and the field Λ, mediated by gravity. There are different terms in the modified general relativistic equation associated to the field Λ; these energy momentum terms modify the local values of the metric of space time and, therefore, give way to perturbed trajectories (geodesics) of particles of matter and radiation. We could say that the wave "guides" the particles. On the other hand, the presence of matter and radiation generates the corresponding associated energy momentum terms, which locally modify the metric of space time. The modified metric appears in the wave equation determining a perturbation of the wave. Particles and wave interact indirectly, mediated by gravity.

It is interesting to notice that in the expression of the scalar curvature

$$R = -\kappa T + \frac{1}{2}g^{\mu\nu}\partial_\mu\Lambda\partial_\nu\Lambda + \frac{\lambda^2}{l_P^2}\Lambda^2 \tag{4}$$

we find positive and negative terms associated to the scalar field, which could represent both dark matter and dark energy. While the energy momentum of matter and radiation vanishes outside its distribution, the terms associated to the field Λ can be distributed along the whole space time.

5. Conclusion

A third (intermediate) system must be introduced to explain the indirect interaction between particle and blocking system in experiments where the wave like behaviour of particles is manifest, and the blocking system breaks this behaviour. The simplest hypothesis is that this new system is a distributed field, de Broglie wave. Although the mathematical model is very speculative, it is interesting to notice how a scalar field obeying a harmonic oscillator variational principle shows an indirect interaction between wave and matter, mediated by gravity. The scalar curvature present both positive and negative terms.

Conflicts of Interest

The author declares no conflicts of interest.

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