Special Relativity:

Understanding the wave-particle duality

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Abstract:

How can interfering light waves transport particle characteristics? Up to now it was supposed that wave-particle duality was a quantum mechanical phenomenon which was not accessible to any classical explanation. The present article is disproving this assumption, by showing o n e single case which is entirely subject to a classical explanation: Photons in vacuum.

The suggested classical explanation of wave-particle duality is simple, and it is deriving directly from special relativity: The particle characteristics are transported directly from A to B, without any intermediate of spacetime, because the interval is zero. The observed wave is a sort of placeholder in our spacetime.

1. Introduction

Up to now, wave-particle duality was considered to be one of the physical phenomena which were not accessible to an intuitive concept[1]: light is interfering as a wave, but simultaneously showing particle character. Wave-particle duality as a manifestation of quantum complementarity seems to prohibit any attempt for classical description. In this article we are proving that wave-particle duality has classical nature, by showing **one** case which may entirely be explained classically. For the first time it is possible to get an intuitive idea of the complementarity of wave-particle duality.

The interest of a classical explanation of wave-particle duality is twofold:

The most obvious profit at stake is the advantage of understanding: the possibility to provide a model of wave-particle duality not only for theoretical research but also for education and for a broader audience, where currently no model is provided for the closer explanation of the principles of wave particle duality.

But the second benefit is not less important: Massless particles in vacuum is a limit case of quantum physics which may be a useful mean for double-checking and for corroborating any hypothesis of quantum mechanics.

2. Two quantum experiments and their explanation

Two key experiments are commonly showing that quantum mechanics is not accessible to classical interpretation:

1. **Young's double slit experiment:** A photon is emitted at A and absorbed at B. Between A and B there is nothing but an interfering light wave, and it is not clear how the particle characteristics have been transmitted.

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[1] See e.g. the citation of Richard Feynman: *"How can a particle go through both slits? Nobody knows, and it's best if you try not to think about it."* **[1]**

2. **Einstein-Podolsky-Rosen thought experiment:** Two photons are entangled at A and measured at B and C where a correlation is stated.

For the case of photons in vacuum, there is an explanation for both experiments: The spacetime interval of the lightlike movement of photons in vacuum is zero **[2] [3]**:

$$\textbf{(1)} \qquad \Delta x^2 + \Delta y^2 + \Delta z^2 - c^2\Delta t^2 = 0$$

This is not an option or interpretation, but a precise, fundamental geometrical principle of spacetime, and it implies that the places of emission and absorption are locally adjacent:

1. In **Young's double slit experiment** the spacetime interval between A and B is empty. No particle characteristics of photons are required because A and B themselves are particles (e.g. electrons), transmitting a momentum without intermediate spacetime.

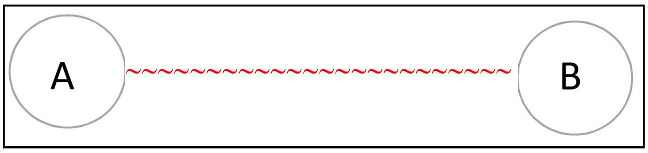


Fig. 1: Space interval between A and B

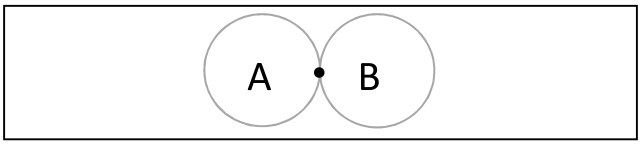


Fig. 2: Spacetime interval of a lightlike worldline between A and B

2. In the **Einstein-Podolsky-Rosen thought experiment** the two spacetime intervals between A and B on one hand and A and C on the other hand are zero. That means that both photons did not leave their respective worldpoint of their entangling process. Thus the observed correlation is not surprising.

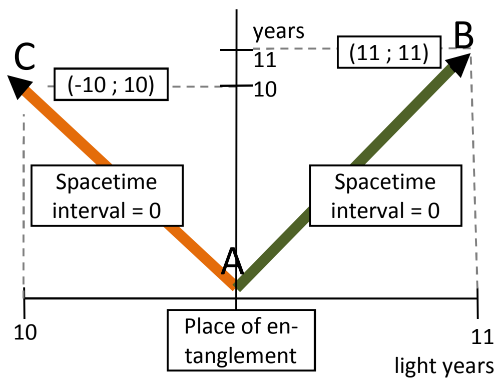


Fig. 3: Minkowski diagram of photon entanglement in vacuum with measurement after 10 years respectively 11 years: Both spacetime intervals are zero.

3. Is an empty spacetime interval an empty interval?

It might be asked if an empty spacetime interval may be considered as equivalent to an empty interval such as an empty space interval.

In order to analyze the physical meaning and the physical effect of an empty spacetime interval we will first consider an example of a contracted spacetime interval:

In a thought experiment, a spaceship has been invented which permits to travel to exoplanets with an average velocity v=0,8c. Question: will it be possible to send a human astronaut to an exoplanet which is situated 100 light years away from Earth?

At first sight this seems impossible because a distance of 100 light years, even traveled at speed of light, requires at least 100 years of service of the astronaut. The exoplanet seems to be out of reach.

But surprisingly it would be possible, due to time dilation and Lorentz contraction.

The reciprocal Lorentz factor γ(v) of v=0,8c is 0,6. That means that time and distance are reduced to 60 percent.

Here are the relevant data concerning time dilation and Lorentz contraction:

		General equation	v = 0,8 c (Space ship)
	Lorentz factor γ, equation **(2)**	$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$	$\gamma = \frac{1}{0{,}6} = 1{,}667$
	Reciprocal Lorentz factor 1/γ **(3)**	$\frac{1}{\gamma} = \sqrt{1-\frac{v^2}{c^2}}$	$\frac{1}{\gamma} = 0{,}6$
Earth reference frame	Distance Earth-exoplanet	*s*	*s* = ***100 light years***
	Traveled time	$v = \frac{s}{t} \Leftrightarrow t = \frac{s}{v}$	$t = \frac{100\ LY}{0{,}8\ c} = \mathbf{125\ years}$
	Velocity	*v*	*v = 0,8 c*
Spaceship's reference frame	Distance Earth-exoplanet, length contraction equation **(4)**	$s' = s\,\frac{1}{\gamma}$	$s' = 100\,years \times 0{,}6 =$ ***60 light years***
	Traveled time, proper time equation **(5)**	$t' = t\,\frac{1}{\gamma}$	$t' = 125\,LY \times 0{,}6 =$ ***75 years***
	Velocity	$v = \frac{s}{t} = \frac{s\prime}{t\prime}$	$v = \frac{100\ LY}{125\ years} = \frac{60\ LY}{75\ years} = 0{,}8\ c$

Fig. 4: Movement of a spaceship near light speed - The astronaut is aging 75 years (spaceship's frame) while traveling a distance of 100 lightyears (Earth frame)

As a result, the exoplanet, although at a distance of 100 light years, can be reached within a possible service life of a human astronaut! The proper time as measured by the astronaut would be 75 years, and from his point of view, the distance Earth - exoplanet would be contracted from 100 to 60 light years.

This example shows that the effects of time dilation and Lorentz contraction have a real effect, and the spacetime interval of a worldline is an interval in the same way as a space interval. For the case v=c the Lorentz factor is not defined (division by zero), massless particles are not subject to Lorentz transformation because they have no inertial reference frame. However, the reciprocal Lorentz factor $1/\gamma$ is reduced to zero, and the calculated proper time of a photon is zero.[2] That implies that the spacetime interval is reduced to zero percent.

In the same way as the contracted spacetime interval permits the astronaut to reach exoplanets which seem to be out of reach with regard to their space interval, the empty spacetime interval permits particle characteristics to be transferred directly from A to B.

4. Interpretation

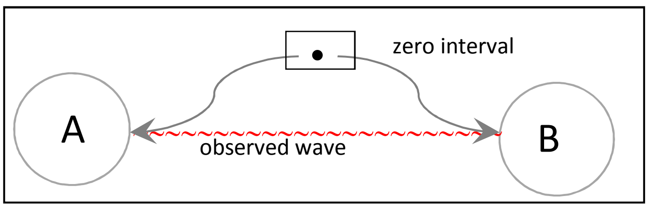
4.1 Deriving the particle characteristics from a wave

According to the Earth reference frame, the photon travels as an electromagnetic wave at v=c 100 light years in 100 years. This is measured by all observers, according to the second postulate of special relativity. The observers are observing the emitting particle A, the absorbing particle B and the photon.

On the other hand, we are searching vainly for a reference frame to which could correspond the zero proper time and the zero spacetime interval we have calculated. - The explanation: The spacetime interval being empty, Earth and the exoplanet are directly adjacent! There is no path, no photon, no movement and no particle between Earth and the exoplanet, and the momentum emitted by Earth is absorbed directly by the adjacent exoplanet, just in the same way as in a particle collision, the momentum of one particle is directly absorbed by the other. The indirect transmission involving 3 particles is replaced by a direct transmission of the momentum from particle A to particle B without intermediate particle.

4.2 Deriving the wave as a side effect of lightlike momentum transfer

While the particle characteristics are arriving at destination via the zero spacetime interval, from the point of view of the observers, there is space between emission and absorption, both events don't seem to be adjacent, they are separated by space. Observers see a separation between the adjacent worldpoints A and B, and instead of the direct momentum transmission they observe an intermediate phenomenon called electromagnetic wave. We can say that electromagnetic waves are acting as subreal "placeholders" at the place of the real pointlike momentum transfer, they must fill the gap because in space, A and B are not directly adjacent.



[2] Partially it is considered that the proper time interval of light signals is zero, e.g. Lawden **[4]**

Fig. 5: Electromagnetic waves are a product of spacetime. For the observer, the zero spacetime interval is "stretched" to the finite space interval of an electromagnetic wave.

The transmission of the momentum happens simultaneously ("double-tracked") as a direct transfer of the momentum and also as the indirect transfer via wave. Both are different aspects of the same dynamical process, and the momentum is transmitted only once in total. In Young's double slit experiment the momentum is passing via the interfering wave through both slits, and simultaneously it is passing directly from A to B via the empty interval.

5. The impact on special relativity

There has been one unexplored zone in special relativity which seemed to give only meaningless results. When particles are moving not only n e a r speed of light (v<c) but a t speed of light (v=c), the Lorentz transforms cease to operate. The proper time is reduced mathematically to zero, but there is no reference system from which this could be observed. Also, due to Lorentz contraction, lengths would be reduced to zero for such a hypothetical non-existent reference system.

This is why up to now the corresponding equations deriving from special relativity (the proper time equation and the length contraction equation, see fig. 4) were considered to be simply confined to massive particles, excluding the case v=c from the domain of definition of these equations. Although there is no physical legitimation for such a break in their application (truncating *de facto* the universality of special relativity), in practice this did not seem to be a big loss for physics.[3][4][5][6]

The question does not depend on Lorentz transformation: The proper time equation and the length contraction equation which are both based on the reciprocal Lorentz factor (proper time equation and Lorentz contraction equation) follow directly from the two postulates of special relativity, without need for the recourse to Lorentz transformation, as shown in 1909 by Gilbert Newton Lewis and Richard C. Tolman by the means of the so-called light-clock. **[9]**

The case v=c is degenerate but not meaningless: Approaching v=>c, 1) the proper time is going to zero, but 2) also the reference frame is vanishing:
1) The reciprocal Lorentz factor is documenting the contraction of the coordinate time to zero proper time.
2) The Lorentz factor is not defined (because of division by zero), showing that any inertial reference frame which could be subject to Lorentz transformation is vanishing.

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[3] Instead of providing a justification for this irregularity, the problem is currently avoided, e.g. Sexl/ Urbantke: Relativity, Groups, Particles: The presentation of special relativity is introduced with Lorentz transformation, and in chapter 2.2 it is simply said that Lorentz transformation is meaningless for v=c. In the further text, photons are only considered with regard to Doppler effect and Compton effect (ch. 4.3). **[5]**

[4] Wolfgang Rindler, Relativity, Special, General, Cosmological, sect. 2.7: "v≥c leads to unphysical transformations" is the only mention of the case v=c. The fact that special relativity does not only consist of Lorentz transformations is not taken into account. Equally, in chapter 4 "Relativistic optics" are mainly described observed effects such as Doppler effect and aberration, but the behavior of the ratio time/ proper time at v=c is not discussed. **[6]**

[5] Landau/ Lifshitz, The Classical Theory of Fields: In § 1.2 Intervals it is stated that the spacetime interval of light signals is zero, and § 1.4 The Lorentz transformation mentions the division-by-zero issue. However § 1.3."Proper time" which has no such issue does not mention the case v=c. **[7]**

[6] Kopeikin, Efroimsky & Kaplan even consider that the result Zero for proper time of lightlike movements makes the result "undefined".**[8]**

6. Outlook with regard to quantum mechanics

Massless particles are not only a model for wave-particle duality, but also for complementarity (1), for the wave function collapse (2) and even for hidden parameters (3) which may be subject to a classical description, by the means of special relativity. Their dynamics comply with local realism (4).

(1) The electromagnetic wave according to Maxwell's equations and the empty spacetime interval are two **complementary** points of view. It is interesting to notice that they are mathematically separated by the reciprocal Lorentz factor γ of special relativity which becomes 0 for movements at c.

(2) The two states before and after the so-called **wave function "collapse"** turn out to be the double-tracked transmission of wave and particle attributes. Instead of the expected collapse we get the double-tracked coexistence of the wave and the "eigenstate" which is incarnated by the transfer of the particle characteristics.

(3) The double-tracked transmission is providing Maxwell's equations with a **hidden parameter**: Each electromagnetic wave is accompanied by a pointlike momentum transmission.

(4) The pointlike direct momentum transmission has no kind of **realism or nonlocality issues**[7] - a momentum is directly transmitted from A to B, and there is no issue of superluminal transmission because A and B are adjacent in spacetime.

7. Conclusion

We are now able to understand precisely and to explain one case (massless particles) of Young's double slit experiment: Special relativity tells us that the particle characteristics going through both slits and the wave are the same physical process.

The direct momentum transmission without intermediate particle via the zero spacetime interval of massless particles is a "missing link" between special relativity and quantum mechanics: On one hand the above-mentioned equations of special relativity (the proper time equation and Lorentz contraction) get rid of the unmotivated restriction of their domain of definition, and on the other hand for quantum interpretations there is provided one deterministic, local answer with regard to the limit case of massless particles.

8. References

[1] Richard Feynman in F. Graham Smith, Terry A. King, Dan Wilkins: Optics and Photonics: An Introduction, 2007

[2] Wolfgang Rindler, Relativity, Special, General, Cosmological, 2001/2006, 3.5 Light cones and intervals

[3] Sexl/ Urbantke: Relativity, Groups, Particles, Springer-Verlag Wien 1992/2001,4.3 Photons: Doppler effect and Compton effect

[7] See in contrast e.g. Kiefer: *"From the experimental violation of Bell's inequalities it has become evident that quantum theory cannot be substituted by a theory referring to a local reality."* **[10]**

[4] Partially it is considered that the proper time interval of light signals is zero, e.g. Lawden, Introduction to Tensor Calculus, Relativity and Cosmology, 1982, p. 150.

[5] Sexl/ Urbantke: Relativity, Groups, Particles, Springer-Verlag Wien 1992/2001.

[6] Wolfgang Rindler, Relativity, Special, General, Cosmological, 2001/2006.

[7] Landau/ Lifshitz, The Classical Theory of Fields, 1951.

[8] Kopeikin, Efroimsky & Kaplan, Relativistic Celestial Mechanics of the Solar System, 2011, p. 275.

[9] The Principle of Relativity and Non-Newtonian Mechanics (1909) Gilbert Newton Lewis and Richard Chace Tolman Proceedings of the American Academy of Arts and Sciences, 1909, 44: 709–726

[10] Claus Kiefer, On the interpretation of quantum theory - from Copenhagen to the present day, 2002, arxiv: quant-ph/0210152v1, p.3.