Numerical simulation of interference experiments in a local hidden variables model.

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We present a theoretical model which allows to keep track of all photons in an interferometer. The model is implemented in a numerical scheme, and we simulate photon interference measurements on one, two, four, and eight slits. Measurements are simulated for the high intensity regime, where we show that our simulations describe all experimental results so far. With a slightly modified concept we can also model interference experiments in the low intensity regime, these experiments have recently been performed with single molecules. Finally, we predict the result of polarization measurements, which allow to check the model experimentally.

I. INTRODUCTION

The problem of interference has haunted modern physics practically from the beginning of the twentieth century. Even though experiments, where a time ordered sequence of single impacts has been recorded, have only recently been developed [1,2], the thought experiments predicting the very same outcome ran into considerable conceptual problems much earlier. For a comprehensive review of the problem see Franco Selleri’s book [3].

The problem can be stated in the following way. Consider a double slit interferometer. Only one particle is thought to propagate from the source to the screen. Therefore the single particle passes a single slit without any interaction with other particles, and impinges on the screen. However, even though the particle cannot be physically influenced by the existence of the second slit, its impact probability at certain spots of the screen depends explicitly on the existence of this second slit. How then, can the particle avoid these spots even though there seems no physical means to that end? For this reason, we do not have a single theoretical model at present, which describes the impact of this particle by a consistent, time ordered sequence of events, along the particle’s path from the source, through the slits and onto the screen, where all interactions are local. The only model, which is capable of such an analysis, is non-local. It is based on David Bohm’s theory of hidden variables [4]. However, this theoretical model depends explicitly on potentials, changing the trajectory of the particle between the slits and the screen, it is therefore unsuitable to describe photon interference measurements.

We wish to close this gap in the present paper by a model, which describes the location of every single photon in the interferometer at every single moment. Moreover, it allows to recover all the results of the experiments while remaining perfectly local. The model has been implemented in a numerical simulation scheme. We perform these simulations mainly for photons, even though a slightly modified model could also account for the recent C60 single-slit interference experiments. The aim of our presentation is to demystify the problem by stating very clearly and in unambiguous terms how the statistical picture arises from limited control in the experiments, and how the physical interactions, which are thought to be deterministic, come into play. It will be seen that the statistical picture underpins the usual treatment in classical field theory, e.g. in the scalar Kirchhoff model, and that it is the very same picture which has been adopted for quantum mechanical purposes. We make one modification to the current understanding of this process, i.e. that the phase of a photon’s field does change discontinuously during the scattering at the slit. And we generally limit the model to the experimentally verified situations, that is to the high intensity regime.

However, the low intensity regime, as in electron interference measurements or recent measurements with molecules, is also discussed extensively. It is shown that in one case one obtains identical results, if the single impacts follow a Gaussian distribution around the actual slits. In the second case, the molecule interference experiments, our investigation is still incomplete but we can make it plausible that a similar model to the one suggested here also accounts for these experiments.

II. THEORETICAL MODEL

In our theoretical description of photon scattering we use essentially Richard Feynman’s path integral method, with a few but decisive modifications. To incorporate the phase of a photon along a given path we describe photons as electromagnetic fields of limited extensions. The compatibility of such a photon model with quantum mechanics has been shown quite some time ago [5]. We omit higher Fourier coefficients, which are due to the confinement of the field, and consider every photon as essentially monochromatic. The field of the photon possesses an arbitrary phase \( \phi_0 \) at the point of emission. This arbitrariness is due to our lack of knowledge about the individual photon. To simplify the model we assume that the fields of all photons are polarized in the same direction, arbitrary polarization only has the effect that the intensity of the beam will have to be higher to obtain
the same effects. The phase of the electromagnetic field of the single photon varies along its optical path from the source to the slit, a difference of $\Delta \phi = 2\pi$ describes two separate points with a distance $\lambda$, the wavelength of the photon. The phase at the slit of our interferometer is therefore $\phi_1 = \phi_0 + 2\pi L_1/\lambda$, where $L_1$ is the distance between the source and the slit.

The scattering of single photons at the slit environment is described by a statistical model. Since currently no theoretical treatment of the problem exists, which would allow us to relate the interaction of the photon with the slit unambiguously to a direction, into which the photon is scattered, we formalize the process in the following way:

The phase $\phi_1$ of the photon together with a random phase $\phi_1$ of the slit environment shall trigger a process which changes the direction of the photon to a scattering angle $\theta_1$. The angles of all photons measured will comply with a Gaussian distribution centered around zero. In practice we have simulated two photons simultaneously, using the phase of the second photon $\phi_1(2)$ as the input from the slit environment $\phi_1(1)$, and vice versa. Since both phases are random, this procedure does not couple the photons in any way, it merely guarantees that the angular distribution after the slit is Gaussian. The halfwidth of the distribution is one of our input parameters. The relevant lines in our code are shown in Appendix A.

Clearly, if the photon changes its direction, then it has interacted with the slit environment. Since we have no deterministic model of this process, we also do not know, what the phase of the photon after the interaction will be. To understand in more detail the nature of this problem, consider the classical scalar model of interference experiments. Here, the scalar field $u(r)$ is thought to be emitted from a point like source. After scattering at the slits it is adsorbed at the screen. Throughout the interferometer the field is at every point in phase with the field at the source. It is thus only by a rigid connection of field amplitudes via the phase that interference effects occur at all within this model.

While such a model works perfectly well for laser beams with their high coherence length and where all photons can be thought to be in phase, it is less appropriate for ordinary monochromatic light. These emissions originate from thermal processes, therefore their phases must generally be random, even though their frequency, e. g. from the decay of an electron excitation in an atom, can be sharply defined. Therefore we explore a different possibility in this paper, and we shall show, that also for a statistical distribution of initial phases interference effects can be obtained, provided the scattering process of a single photon at one slit changes the phase of the photon discontinuously. It goes without saying that the results are the same, if we use monochromatic laser light instead of monochromatic light from emissions of thermally excited atom.

In our model, as indeed in every model which constructs interferences from uncorrelated photons, the single photon will have an arbitrary phase at the source. Moreover, the phase of the photon is not connected to the phase of any other photon. Therefore, if we adopt the view that the field of the single photon remains in-phase with the field at its source, we will not describe any interference effects. We conclude from this fact that the field cannot remain in phase. Since the photon interacts only at one point of our system, at the slit of the interferometer, it can only be this point, where the phase changes.

Here, we make the only truly novel conjecture in this paper: the phase angle $\phi_1'$, after the scattering process, shall be proportional to the angle, into which the photon is scattered:

$$\phi_1' = \alpha \theta_1$$

For reasons of consistency we choose the constant $\alpha$ equal to one. The conjecture can then be linked to the description of field deflection in classical electrodynamics, where a reflection of a field at a surface leads to a change of its phase by $\pi$. Since in classical field theories the phase is continuous throughout the system, the phase shift is related to changes throughout the system. In case of arbitrary initial phases we can only recover this feature, if we set the phase itself equal to the angle of scattering. In our view this model is a generalization of classical concepts to the case, where we have given up the rigid connection of fields throughout the system.

The photons are scattered at a single slit and propagate in a straight line towards the detector screen. Here, the fields of individual photons are superimposed and the total field at a point $P(x,y)$ is given by the expression:

$$E(x, y) = \sum_{i=1}^{n} \cos(\phi_2(i))$$

where $n$ is the total number of photons impinging at this point, and $\phi_2$ is the phase at their moment of impact. The phase is related to the scattering angle $\theta_1$ by the expression:

$$\phi_2 = \theta_1 + 2\pi \frac{\sqrt{L^2 + y^2}}{\lambda} \quad \frac{y}{L} = \tan \theta_1$$

Here $L$ is the distance between the plane of the slits and the plane of the detector screen. The details of the model are displayed in Fig. 1. The intensity at the point $P(x,y)$ of the detector screen is consequently:

$$I(x, y) = E(x, y)^2$$

The intensity we observe is thus the intensity due to the total field after superposition of all contributions. It is for this reason that the model is generally limited to the high intensity regime. However, we will indicate in the discussion, how a slightly modified version of the same model can also account for single molecule interferences.
Furthermore, we shall demonstrate that single electron experiments, where a periodic image is gradually evolving, can be understood without the occurrence of any superpositions from separate slits and thus without interferences proper.

III. NUMERICAL IMPLEMENTATION

The theoretical model requires a random input at two points of the interferometer: (i) at the emission of a photon from the source; and (ii) at the scattering of the photon at the slit environment. We have used a random number generator for both processes, mapping the random number [0,1] onto the initial phase [0,2\(\pi\)]. The dimensions of the apparatus were chosen similar to an experimental one. We also chose monochromatic visible light of \(\lambda = 500\text{nm}\). The distance \(d\) between two slits of the interferometer equals 0.5 \(\mu\text{m}\). The distance \(L\) between the source and the slit and the slit and the screen in our simulations was 10\(\text{mm}\) (see Fig. 1).

The simulation of an experimental run is straightforward. For a pair of photons, we create the initial phases \(\phi_0(1,2)\), and compute the phase after covering the distance to the slit. Here, we use the phase of the second photon \(\phi_1(2)\) as the random phase of the slit environment for photon one and vice versa. The two random inputs are used to create two random outputs, which now comply with a Gaussian distribution (see Appendix A). This Gaussian distribution describes the scattering angle of the photons after the slit. The phase angle of the photons at this point is set equal to the scattering angle, and both photons propagate until they hit the screen. We record the points of impact and the phases at the moment of impact, before simulating the next pair. In all our simulations we simulated 100000 photons per slit.

We have assumed that the slit is very narrow, in practice we have always used the same point as the slit position. The simulation method has been tested for slits of variable width, but apart from a blurred image due to the variable position of the photons in the plane of the slits we did not obtain any new feature compared to the results obtained with a very narrow slit. Since the slit width is generally unknown we have omitted this part of the numerical analysis.

To evaluate the photon impacts we have assumed that photons interact if their distance is less than 10 \(\text{nm}\) on our detector screen. This is no limitation of the generality of our model, since we could always increase the number of photons and thus allow for higher resolution. The total field at each of these separate points was calculated and then smoothed with a Gaussian of 0.1 \(\mu\text{m}\) halfwidth. The plots of the number of photons and the intensity are shown in units of \(I_0\), the maximum intensity, and \(N_0\), the maximum number of impacts.

We have also accounted for a numerical problem in the transition from single slit diffraction to multiple slit interferometry. In a single slit, and assuming that the scattering angle is equal to the phase angle, the intensity distribution of the photons on the screen is essentially due to the intensity distribution of the photon fields. All photons, at a given point, will have the same phase. This is not the case in a multiple slit interferometer. Here we have to sum up contributions from different slits, and the total intensity is due to the total electromagnetic field.

The critical points at the screen, in a numerical model, are the points where the phase difference between separate slits yields constructive interference, while the phase from one single slit, or the effect of photon diffraction, yields a minimum of the field. For a double slit interferometer, the cos\(\phi_2\) at the median point between two slits is zero (because \(\phi_2 \approx \pi/2\)), while the interference between the two separate slits is constructive (because both phases are equal). Since it is largely a matter of convention in field physics, whether a constant phase is added in all calculations, we have used the same approach in this numerical model. For multiple slit simulations we therefore have increased the final phase \(\phi_2\) by a value of 0.2\(\pi\) and for every single photon.

IV. RESULTS

The main results of our simulations are shown in Figs. 2 to 8. In all plots we show the normalized impact numbers (dash dotted grey curve) as well as the normalized intensity distribution (black curve). The position of the slits is indicated by a dash dotted vertical line. We also show a simulated greyscale image of the detector screen, this filmstrip describes how the image would look in a real interferometer.

The height of the peaks depends, for a given number of slits, essentially on the halfwidth \(\sigma\) of the scattering angles. Since this parameter reflects the actual experimental situation, or rather the unknown scattering process in the slit environment, we cannot set it to a theoretically required value. For this reason we can only change it so that the results of our simulation are in accordance with experimental data. In consequence the absolute value of a specific peak reflects to a certain extent our choice of parameters. But the change of the peak height, e.g. if a double slit and a four slit image are compared, does not depend on our settings, it is a genuine consequence of the theoretical assumption that the interference pattern is built up by superposition of the electromagnetic fields of independent photons.

Analyzing the difference between a single slit diffraction and double slit interference (Fig. 2 and Fig. 3), it becomes immediately clear why, in the first case, the peak is at the position of the slit, while in the second case it indicates the median position between the two slits. This is simply due to the interference of photons passing through different slits, which leads to destructive interference at both slit positions, thus creating the
distinct intensity minima. In Fig. 4 we show, how the distance between the slits and the halfwidth effect the intensity distribution. For this image we have increased the distance between the slits to 2λ, the halfwidth σ is now 1.5. The number of observed peaks in this case is substantially increased. The image is equal to the experimental images obtained in a Young interferometer.

The effect of destructive interference leads to an interesting phenomenon, if the fringes for two and four slits are compared. Because in the latter case (Fig. 5) the peak at the center of the screen is reduced, it seems thus that the opening of two new slits effectively decreases the number of impinging photons. As the number distribution reveals, this is clearly not the case. The intensity is reduced due to destructive interference of the electromagnetic fields carried by each individual photon. Generally speaking the intensity peaks become more and more similar with an increasing number of slits, so that in the limit of infinite slits, or an infinite chain of slits, the intensity distribution would be purely periodic while the distance between the peaks is equal to the distance between the slits. This is, what we actually observe in diffraction experiments with either photons (x-ray diffraction), or electrons (electron diffraction).

Comparing the distribution of photon impacts with the intensity distribution, it is clear that the main feature, which creates the interference pattern, is the loss of intensity at certain points of the detector screen. These points are due to destructive interference, in the multiple slit interferometer, or to minima of the photon fields, in the single slit interferometer. We take this as a general result of our simulation: periodic intensity distributions in a process, or interference fringes, are always due to a loss of intensity at specific points.

Our records of the simulation contain the information about each individual photon: its trajectory and its phase at the moment of impact. Information, which according to the current understanding prohibits the interference of photons from different slits (this is the principle of the so called which-path or welcher Weg experiments). Here, we retain all the information and still find an interference pattern.

This is due to the fact that the vanishing interference pattern in a Welcher Weg experiment is no consequence of the information about the path of the photon, but, in the way the experiment is often implemented, due to the vanishing superposition of the photon’s electromagnetic fields. In practice, such an experiment can be carried out with polarized photons in a two slit interferometer, if photons of horizontal (vertical) polarization pass only through the first (second) slit. If we simulate this situation, then we have to account for the vector characteristics of photon polarization. This, in turn, means that the electromagnetic field of the horizontally polarized photons is perpendicular to the electromagnetic field of the vertically polarized photons. And then the superposition of the fields occurs independently, and in two dimension, the two directions perpendicular to the photon’s vector of motion. The result of this simulation is shown in Fig. 6. The two single slits are still clearly visible, the maxima, furthermore, are at the position of the slits, clearly photons from one slit have not interacted with photons from the other slit. The typical two slit interference pattern can be made to reappear by inserting a diagonal polarizer into the path of all photons: since all photons then have the same vector of polarization, the superposition occurs again only in one dimension and the interference pattern is recovered.

V. DISCUSSION

The local model has two key ingredients: a local scattering event at a single slit, where the photon is scattered into a new direction, and a local superposition at the focal plane of the interferometer, where the electromagnetic fields of single photons are superimposed. The second feature, the local superposition of fields, is also the main feature of classical models of interference. It is, as David Deutsch remarked in his book [9], also the main issue in quantum mechanical models, even though not every photon can be thought to be real in every situation. One has to conclude, therefore, that no model exists, which predicts interference effects from the scattering events alone. This would imply a non-local connection between the individual slits. Theoretically speaking we have no reason to believe that such a model is physically meaningful. Therefore, even given the present results, the conceptual problem in the low intensity regime still seems to prevail. To our knowledge these low intensity experiments so far have only been performed with electrons, and C60 molecules [10]. We are currently investigating the experiments with C60 molecules and the emerging picture is roughly the following: due to its high energy the molecule possesses a considerable dipole moment, which oscillates along its path. This oscillating moment plays the same role as the periodic electromagnetic field of a photon. In the slit environment the molecule is scattered into a new direction due to interaction between the molecule and the atoms of the slit. The scattering angle depends on the phase of the molecular dipole moment. The molecule can only be detected after ionization. Since the ionization process will not be successful in every case, not all molecules will actually be detected. And if the success rate of ionization depends on the dipole moment of the molecule, then the angle of scattering is linked to the probability of detection. We will present the exact numerical results for this experiments in a future publication.

The impact of single electrons gradually building up the interference pattern of the statistical theory, as in Tonomura’s 1989 experiments, seems to be the strongest proof, that a single electron undergoes interference on the screen, even though there is no other electron present, which could do the trick. In the view of the Many Worlds
interpretation of quantum mechanics [10], the electron in this case interacts with an electron from a parallel universe, a 'shadow' electron. As already mentioned, there is so far no unambiguous proof that the same behavior can be seen for single photons: photon interference measurements have only been performed in the high intensity regime. This makes electron interferences all the more important. And, if these experiments are correct, then it could be seen as a demonstration of the validity of the Many Worlds interpretation. However, an identical result can be obtained, if the single electrons do not interact with 'shadow' electrons, but if the angular distribution of scattered electrons after the slit system is very narrow. So narrow, in fact, that the overlap between the impact of electrons from separate slits is close to zero. We have simulated such a measurement with photons, an identical result could be obtained for electrons if the lengths are reduced by three orders of magnitude. As seen in Fig. 2, the peaks of the number distribution coincide with the peaks of the intensity distribution. This is fundamentally different from the previous cases, where the intensity peaks were always between the positions of single slit. It is, in short, the proof that there is no interference at work under these conditions. The periodic distribution at the screen is merely an image of the periodic arrangement of slits of the interferometer.

Following this line of research, it is also possible that the experiments with single C60 molecules [3] are no indication of any phase effects at all, but simply due to a specific choice of experimental parameters. If we assume that the initial molecular beam before the slit system is wider than the distance between the single slits, so that molecules will pass through the central slit and two side-slits, then the image on the screen will show one main peak between two smaller peaks. Apart from determining the absolute position of the image in relation to the central slit, there is no way to decide, whether we deal with interference, or just a statistical distribution of molecule impacts due to their passing through the slit system. We have simulated this situation by counting the impacts of single photons, if 40% of the photons pass through a side-slit. The Gaussian in this case was assumed to be narrow enough to retain the side peaks as distinct features. This can essentially be obtained in an experiment with molecular beams by making the molecular velocity high enough. The result of this simulation is shown in Fig. 3. It can be seen that the essential features of the experimental image - one main peak, two side peaks, the visibility of the minima very low - are recovered if the parameters are suitably chosen. Also in this situation we do not deal with interference, but merely with the impact of particles scattered at the slit system.

This simple model can easily be checked experimentally. Since the occurrence of "interference fringes" depends on the statistical spread and thus the velocity of the C60 molecules, the fringes should disappear, if the velocity decreases below a certain threshold. In fact, the predictions of the model can be tested by varying the velocity. We predict that the visibility depends on molecular velocity, while in interference experiments proper the position of the maxima and minima depends on the velocity. If the intensity distribution is only due to kinetic effects, then the positions will not be altered by a variation of velocity.

Let us go back to our analysis of the double-slit interferometer in the introduction and to the problem, how photons can avoid regions of low intensity on the detector screen. It becomes clear now, that this is actually not the case. The number density of photons on the screen in all cases of physical interference is more or less Gaussian. The periodicity of the intensity, the observed interference pattern, is only due to interference between the fields of individual photons. The number density, therefore, is generally not related to the intensity distribution. It appears thus that quantum mechanics, which arrives at an oscillating number density (the probability distribution $|\psi|^2$) to account for the intensity in interference experiments, gives a misleading and even wrong account of the actual physical situation.

VI. EXPERIMENTAL TESTS

The conjecture used to construct the local model also for a random distribution of photon phases has interesting consequences, which can in principle be checked experimentally. Consider an experiment with polarized monochromatic light. Then after the slit the direction into which a photon is scattered is related to the phase after the interaction with the slit environment. Therefore photons at different points of the detector screen will have different phases. The difference between e.g. the first and second maximum in a double slit interferometer (see Fig. 8) corresponds to a phase difference of

$$\Delta \phi \approx \pi$$

(5)

For polarized photons, this difference can be measured with an optical modulator, since the phase at the front end of the modulator determines the rotation of the field vector $|1\rangle$. Subjecting photons after the modulator to a polarization measurement should yield a different result for photons impinging at different points of the detector screen.

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APPENDIX A

The actual code fragment, which transforms a uniform distribution [0,1] into a Gaussian distribution \(\exp(-x^2/2)\) includes only 15 lines. The main features are: first create a random number PHASE1, add the phase from the propagation to the slit, and throw away multiples of one (or of \(2\pi\)): this random number is now transformed from the interval [0,1] (PHI1) to the interval [-1,1] (V1):

```
10 PHASE1 = RANDOM()
PHI1 = PHASE1 + Z
K = PHI1
PHI1 = PHI1 - FLOAT(K)
V1 = 2.*PHI1 - 1.
```

Now do the same for a second number PHASE2, which results in V2:

```
PHASE2 = RANDOM()
PHI2 = PHASE2 + Z
K = PHI2
PHI2 = PHI2 - FLOAT(K)
V2 = 2.*PHI2 - 1.
```

Calculate the radius and see, whether it is inside the halfwidth of the desired Gaussian: if it is, then compute the final values, if it is not, then choose two new random numbers:

```
RADIUS = V1*V1+V2*V2
IF (RADIUS.GT.1.0) GOTO 10
FACTOR = SQRT(-2.*LOG(RADIUS)/RADIUS)
GAUSS1 = V1*FACTOR
GAUSS2 = V2*FACTOR
```

These two variables, GAUSS1 and GAUSS2, which comply with a Gaussian of halfwidth one, are then multiplied by our input parameter \(\sigma\), the chosen Gaussian halfwidth of our angular distribution. In the simulations the halfwidth was set to \(6 \times 10^{-5}\).

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FIG. 1. Model interferometer in our numerical simulations. (A) The photon is emitted from the source with an initial phase $\phi_0$. (B) The acquired phase of the photon $\phi_1$ and a random phase of the slit environment determine the scattering angle $\theta_1$. The phase after the scattering process changes discontinuously to $\phi'_1$. (C) The photon hits the detector screen and interacts with other photons impinging at the same location.

FIG. 2. Single slit diffraction on very narrow slit. The intensity (black curve) shows a distinct main peak and two side peaks. The periodic feature is due to superposition of the fields of single photons, the number density (grey dashed curve) only displays the Gaussian distribution of the scattering angles. In the filmstrip we show how the image would look in a diffractometer.

FIG. 3. Double slit interference. The main peak is between the position of the two slits, the plot shows the main peak and two side peaks. Note that the maxima at the position of the slits have vanished due to destructive interference of photons from different slits.

FIG. 4. Double slit interference with increased slit-distance ($d = 2\lambda$) and increased halfwidth ($\sigma = 1.5 \times 10^{-4}$). The distance between maxima and minima, which is only due to the differences of the optical path for individual photons remains constant, the number of observed peaks is substantially increased.

FIG. 5. Four slit simulation. The image shows two main peaks separated by a minor peak of the intensity distribution. Comparing with the two slit image the main peak of the intensity distribution seems to be reduced. This is due to destructive interference of photons from the outer slits.
FIG. 6. Eight slit simulation. The intensity of all five inner maxima is roughly equal, the distribution of maxima and minima images the slits of the interferometer, even though all maxima are between the positions of individual slits.

FIG. 7. Welcher Weg experiment with two slit interferometer. The photons are either horizontally (slit 1) or vertically (slit 2) polarized. Due to the vector characteristics of the electromagnetic fields only photons from the same slit interfere for with each other. The double slit image, obtained if all photons possess equal polarization, is lost (compare the image Fig. 3).

FIG. 8. Eight slit simulation with reduced angular distribution after scattering. The impact regions of photons from different slits overlap only in a minor way. In consequence, the periodic distribution of intensity is no indication of interference effects, even though the image looks similar to an eight slit interferometer image (compare Fig. 6).

FIG. 9. Simulation of photon impacts in a three slit system with reduced beam width and reduced angular distribution after scattering. The impact count reproduces all the features of the experiments with single C60 molecules. Also in this case the distribution of intensity is no indication of interference effects.