Quantum theory of two-photon interference

Xiang-Yao Wu\textsuperscript{a} *, Bo-Jun Zhang\textsuperscript{a}, Xiao-Jing Liu\textsuperscript{a}, Hong Li\textsuperscript{a}
Si-Qi Zhang\textsuperscript{a}, Jing Wang\textsuperscript{a}, Yi-Heng Wu\textsuperscript{b} and Jing-Wu Li\textsuperscript{c}
\textsuperscript{a}. Institute of Physics, Jilin Normal University, Siping 136000, China
\textsuperscript{b}. College of Physics, Jilin University, Changchun 130000, China
\textsuperscript{c}. Institute of Physics, Xuzhou Normal University, Xuzhou 221000, China

In this paper, we study two-photon interference with the approach of photon quantum theory, with specific attention to the two-photon interference experiment carried out by Milena D'Angelo et al. \textit{(Phys.Rev.Lett87 : 013602, 2001)}. We find the theoretical result is accordance with experiment data.

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1. Introduction

Nonclassical interference is one of the most remarkable phenomena in quantum optics. In particular, it can be observed in experiments with spontaneous parametric down conversion (SPDC) \cite{1}, a nonlinear optical process in which high-energy pump photons are converted into pairs of low-energy photons (usually called signal and idler) inside a crystal with quadratic nonlinearity. It has been shown in many experiments that the quantum state of the signal-idler photon pair is entangled \cite{2}. Many experiments have made use of SPDC to demonstrate fascinating topics in quantum optics, such as the test of Bell's inequalities, quantum communication, quantum teleportation, etc. \cite{3}, and its possible applications include quantum communication, computation, and cryptography \cite{4}. All these experiments basically belong to the same category: quantum interference. Two-photon interference is one of the pure quantum phenomena attributed to quantum correlations. In experiments on two-photon interference, each photon pair behaves like a quantum object called a "biphoton", whose effective energy (or frequency) is twice that of the original photons, and the interference fringe of the photon pair has half the period of a one-photon interference fringe.

Two-photon interference is a powerful tool to study the fundamental problems of quantum theory. For example, the Einstein-Podolsky-Rosen problem \cite{5} is believed to be resolvable by testing Bell's inequality \cite{6} and the Greenberger-Horne-Zeilinger theorem \cite{7} in two-photon or multiphoton interference experiments. Two-photon interferometry also has broad applications in practical areas such as quantum cryptography \cite{8}, metrology \cite{9}, potentially in quantum computing \cite{10}, precision metrology, information processing and imaging Coincidence imaging, or ghost imaging \cite{11, 12}.

Recently it has been argued that classically correlated light might mimic some features of the entangled photon pairs in coincidence imaging setups. Notice that the possibility of simulating the two-photon imaging features of entangled states with classical sources was not ruled out by the authors of the original ghost imaging experiment \cite{13}. Both the theoretical work of Abourraddy et.al. \cite{14} and the experimental investigation of Bennink et.al. \cite{15} stimulated a very interesting debate about the role of entanglement in two-photon coincidence imaging \cite{16}. In this work, we study the two-photon interference with the approach of relativistic quantum theory of photon. In the viewpoint of quantum theory, the light has the nature of wave, and it is described by wave function $\psi(\mathbf{r}, t)$ for the photon of spin 1. The absolute square $|\psi(\mathbf{r}, t)|^2$ can be explained as the photon’s probability density at the definite position. For light interference and diffraction, the interference and diffraction intensity $I$ is directly proportional to $|\psi(\mathbf{r}, t)|^2$ distributing on display screen, and the light wave functions can be divided into three areas. The first area is the incident area, where the photon wave function is a plane wave. The second area is the slit area, where the light wave function can be calculated by quantum wave equation of photon. The third area is the diffraction area, where the

* E-mail: wuxy2066@163.com
light wave function can be calculated by the Kirchoff’s law. For double-slit interference, we can obtain the total diffraction wave function by superposition of the diffraction wave function of every slit. For two-photon double-slit interference, we calculate the total interference wave function \( \vec{\psi}(\vec{r}, t) = c_1 \vec{\psi}_1(\vec{r}, t) + c_2 \vec{\psi}_2(\vec{r}, t) \) and \( \vec{\psi}_i(\vec{r}, t) = c_3 \vec{\phi}_1(\vec{r}, t) + c_4 \vec{\phi}_2(\vec{r}, t) \) for the signal and idler photon, and the detectors \( D_1 \) and \( D_2 \) measure the interference intensities are directly proportional to \( |\vec{\psi}_s(\vec{r}, t)|^2 \) and \( |\vec{\psi}_i(\vec{r}, t)|^2 \) for the signal and idler photon, respectively. The intensity of coincidence measurement is directly proportional to \( |\vec{\psi}_s(\vec{r}, t) \cdot \vec{\psi}_i(\vec{r}, t)|^2 \) for two-photon double-slit interference. In the following, we shall calculate these wave functions, and compare the calculation result with the experiment.

2. Quantum approach of photon single-slit diffraction

In an infinite plane, we consider a single-slit, its width \( a \) and length \( b \) are shown in FIG. 1. The \( x \) axis is along the slit length and the \( y \) axis is along the slit width \( a \). In the following, we calculate the light wave function in the single-slit with relativistic wave equation. At time \( t \), we suppose that the incident plane wave travels along the \( z \) axis. It is

\[
\psi_0(z, t) = \vec{A} e^{i \hbar (pz - Et)}
= \sum_j A_j \cdot e^{i \hbar (pz - Et)} \vec{e}_j
= \sum_j \psi_{0j} \cdot e^{-i \hbar Et} \vec{e}_j,
\]

where \( \psi_{0j} = A_j \cdot e^{i \hbar pz}, j = x, y, z \) and \( \vec{A} \) is a constant vector. The time-dependent relativistic wave equation of light is [12]

\[
i \hbar \frac{\partial}{\partial t} \vec{\psi}(\vec{r}, t) = c \hbar \nabla \times \vec{\psi}(\vec{r}, t) + V \vec{\psi}(\vec{r}, t),
\]

where \( c \) is light velocity. From Eq. (2), we can find the light wave function \( \vec{\psi}(\vec{r}, t) \rightarrow 0 \) when \( V(\vec{r}) \rightarrow \infty \). The potential energy of light in the single-slit is

\[
V(x, y, z) = \begin{cases} 0 & 0 \leq x \leq b, 0 \leq y \leq a, 0 \leq z \leq c' \\ \infty & \text{otherwise} \end{cases}
\]

where \( c' \) is the slit thickness. We can get the time-dependent relativistic wave equation in the slit \( V(x, y, z) = 0 \), it is

\[
i \hbar \frac{\partial}{\partial t} \vec{\psi}(\vec{r}, t) = c \hbar \nabla \times \vec{\psi}(\vec{r}, t),
\]

by derivation on Eq. (4) about the time \( t \) and multiplying \( i \hbar \) both sides, we have

\[
(i \hbar)^2 \frac{\partial^2}{\partial t^2} \vec{\psi}(\vec{r}, t) = c \hbar \nabla \times i \hbar \frac{\partial}{\partial t} \vec{\psi}(\vec{r}, t),
\]
substituting Eq. (4) into (5), we have
\[
\frac{\partial^2 \tilde{\psi}(r, t)}{\partial t^2} = -c^2[\nabla(\nabla \cdot \tilde{\psi}(r, t)) - \nabla^2 \tilde{\psi}(r, t)],
\] (6)
where the formula \( \nabla \times \nabla \times \vec{B} = \nabla(\nabla \cdot \vec{B}) - \nabla^2 \vec{B} \). From Ref. [11], the photon wave function is \( \vec{\psi}(\vec{r}, t) = \sqrt{\varepsilon_0^2(\vec{E}(\vec{r}, t) + i\sigma c\vec{B}(\vec{r}, t))} \), we have
\[
\nabla \cdot \vec{\psi}(r, t) = 0,
\] (7)
from Eq. (6) and (7), we have
\[
\left( \frac{\partial^2}{\partial t^2} - c^2 \nabla^2 \right) \vec{\psi}(r, t) = 0.
\] (8)
The Eq. (8) is the same as the classical wave equation of light. Here, it is a quantum wave equation of light, since it is obtained from the relativistic wave equation (2), and it satisfied the new quantum boundary condition: when \( \vec{\psi}(\vec{r}, t) \to 0, V(\vec{r}) \to \infty \). It is different from the classic boundary condition.

When the photon wave function \( \vec{\psi}(\vec{r}, t) \) change with determinate frequency \( \omega \), the wave function of photon can be written as
\[
\vec{\psi}(\vec{r}, t) = \vec{\psi}(\vec{r}) e^{-i\omega t},
\] (9)
substituting Eq. (9) into (8), we can get
\[
\frac{\partial^2 \vec{\psi}(r)}{\partial x^2} + \frac{\partial^2 \vec{\psi}(r)}{\partial y^2} + \frac{\partial^2 \vec{\psi}(r)}{\partial z^2} + \frac{4\pi^2}{\lambda^2} \vec{\psi}(r) = 0,
\] (10)
and the wave function satisfies boundary conditions
\[
\vec{\psi}(0, y, z) = \vec{\psi}(b, y, z) = 0,
\] (11)
\[
\vec{\psi}(x, 0, z) = \vec{\psi}(x, a, z) = 0.
\] (12)
The photon wave function \( \vec{\psi}(\vec{r}) \) can be wrote
\[
\vec{\psi}(\vec{r}) = \psi_x(\vec{r})e^x + \psi_y(\vec{r})e^y + \psi_z(\vec{r})e^z = \sum_{j=x,y,z} \psi_j(\vec{r})e^j,
\] (13)
where \( j \) is \( x, y \) or \( z \). Substituting Eq. (13) into (10), (11) and (12), we have the component equation
\[
\frac{\partial^2 \psi_j(\vec{r})}{\partial x^2} + \frac{\partial^2 \psi_j(\vec{r})}{\partial y^2} + \frac{\partial^2 \psi_j(\vec{r})}{\partial z^2} + \frac{4\pi^2}{\lambda^2} \psi_j(\vec{r}) = 0.
\] (14)
\[
\psi_j(0, y, z) = \psi_j(b, y, z) = 0,
\] (15)
\[
\psi_j(x, 0, z) = \psi_j(x, a, z) = 0.
\] (16)
The partial differential equation (14) can be solved by the method of separation of variable. By writing
\[
\psi_j(x, y, z) = X_j(x)Y_j(y)Z_j(z).
\] (17)
From Eq. (14), (15), (16) and (17), we can get the general solution of Eq. (14)

\[ \psi_j(x, y, z) = \sum_{m,n} D_{mnj} \sin \frac{m\pi y}{a} e^{i\sqrt{\frac{4\pi^2}{\lambda^2} - \frac{n^2\pi^2}{b^2} - \frac{m^2\pi^2}{a^2}} z}, \quad (18) \]

since the wave functions are continuous at \( z = 0 \), we have

\[ \psi_0(x, y, z; t) \mid_{z=0} = \psi(x, y, z; t) \mid_{z=0}, \quad (19) \]

or, equivalently,

\[ \psi_0(x, y, z) \mid_{z=0} = \psi(x, y, z) \mid_{z=0}. \quad (j = x, y, z) \quad (20) \]

From Eq. (1), (18) and (20), we obtain the coefficient \( D_{mnj} \) by fourier transform

\[ D_{mnj} = \frac{4ab}{\pi^2} \int_0^a \int_0^b A_j \sin \frac{n\pi \xi}{b} \sin \frac{m\pi \eta}{a} d\xi d\eta \]

\[ = \begin{cases} \frac{16A_j}{mn\pi^2} & m, n, \text{odd} \\ 0 & \text{otherwise} \end{cases}, \quad (j = x, y, z) \quad (21) \]

substituting Eq. (21) into (18), we have

\[ \psi_j(x, y, z) = \sum_{m,n=0}^\infty \frac{16A_j}{(2m+1)(2n+1)\pi^2} \sin \frac{(2m+1)\pi x}{b} \sin \frac{(2n+1)\pi y}{a} e^{i\sqrt{\frac{4\pi^2}{\lambda^2} - \frac{(2m+1)^2\pi^2}{a^2} - \frac{(2n+1)^2\pi^2}{b^2}} z}, \quad (j = x, y, z) \quad (22) \]

substituting Eq. (22) into (9) and (13), we can obtain the photon wave function in slit

\[ \tilde{\psi}(x, y, z; t) = \sum_{j=x,y,z} \psi_j(x, y, z; t) e^{i\epsilon_j} \]

\[ = \sum_{j=x,y,z} \sum_{m,n=0}^\infty \frac{16A_j}{(2m+1)(2n+1)\pi^2} \sin \frac{(2m+1)\pi x}{b} \sin \frac{(2n+1)\pi y}{a} e^{i\sqrt{\frac{4\pi^2}{\lambda^2} - \frac{(2m+1)^2\pi^2}{a^2} - \frac{(2n+1)^2\pi^2}{b^2}} z} e^{-i\omega t} e^{i\epsilon_j}. \]

\( (23) \)

We can consider the case of limit, i.e., the slit length \( b \) is infinity, and the Eq. (8) and (10) become

\[ \frac{\partial^2 \tilde{\psi}(y, z, t)}{\partial y^2} - c^2 \left( \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \tilde{\psi}(y, z, t) = 0, \]

\[ (24) \]

\[ \frac{\partial^2 \tilde{\psi}(y, z)}{\partial y^2} + \frac{\partial^2 \tilde{\psi}(y, z)}{\partial z^2} + \frac{4\pi^2}{\lambda^2} \tilde{\psi}(y, z) = 0, \]

\[ (25) \]

we can easily obtain the light wave function in the single-slit when \( b \to \infty \)

\[ \tilde{\psi}(y, z; t) = \sum_{j=x,y,z} \psi_j(x, y, z; t) e^{i\epsilon_j} \]

\[ = \sum_{j=x,y,z} \sum_{m=0}^\infty \frac{4A_j}{(2m+1)\pi} \sin \frac{(2m+1)\pi y}{a} e^{i\sqrt{\frac{4\pi^2}{\lambda^2} - \frac{(2m+1)^2\pi^2}{a^2}} z} e^{-i\omega t} e^{i\epsilon_j}. \]

\[ (26) \]
3. The wave function of photon diffraction

In the section 2, we have calculated the photon wave function in slit. In the following, we will calculate diffraction wave function. we can calculate the wave function in the diffraction area. From the slit wave function component $\psi_j(\vec{r},t)$, we can calculate its diffraction wave function component $\Phi_j(\vec{r},t)$ by Kirchhoff’s law. It can be calculated by the formula[17]

$$\Phi_j(\vec{r},t) = -\frac{1}{4\pi} \int_{s_0} e^{ikr} \vec{n} \cdot [\vec{\nabla} \psi_j + (ik - \frac{1}{r}) \vec{r} \psi_j] ds. \quad (27)$$

the total diffraction wave function is

$$\tilde{\Phi}(\vec{r},t) = \sum_{j=x,y,z} \Phi_j(\vec{r},t) \vec{e}_j, \quad (28)$$

the diffraction area is shown in FIG. 2, where $k = \frac{2\pi}{\lambda}$ is wave vector, $s_0$ is the area of the single-slit, $\vec{r}'$ the position of a point on the surface ($z = c'$), $P$ is an arbitrary point in the diffraction area, and the $\vec{n}$ is a unit vector, which is normal to the surface of the single-slit. From FIG. 2, we have

$$r = R - \frac{\vec{R}}{R} \cdot \vec{r}'$$
$$\approx R - \frac{\vec{r}}{r} \cdot \vec{r}'$$
$$= R - \frac{k^2}{k} \cdot \vec{r}', \quad (29)$$

then,

$$\frac{e^{ikr}}{r} = \frac{e^{ik(R-\frac{\vec{r}}{r} \cdot \vec{r}')}}{R - \frac{\vec{r}}{r} \cdot \vec{r}'}$$
$$\approx \frac{e^{ikR}e^{-i\vec{r} \cdot \vec{r}'}}{R} \quad (|\vec{r}'| \ll R), \quad (30)$$

FIG. 2: The diffraction area of single-slit
where \( \vec{k}_2 = k \vec{z} \). Substituting Eq. (22), (29) and (30) into (27), one can obtain

\[
\Phi_j(r', t) = -\frac{e^{ikR}}{4\pi R} e^{-i\omega t} \int_{s_0} e^{-ik_2} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{16A_j}{(2m+1)(2n+1)^2 \pi^2} e^{i \sqrt{\frac{4\pi^2}{\lambda^2} - \left(\frac{2m+1}{b} \pi\right)^2} c'} \sin \left(\frac{(2n+1)\pi}{b} x\right) \sin \left(\frac{(2m+1)\pi}{a} y\right) \int_{[i \sqrt{\frac{4\pi^2}{\lambda^2} - \left(\frac{2m+1}{b} \pi\right)^2} - \left(\frac{2m+1}{a} \pi\right)^2} c'] \sin \left(\frac{(2n+1)\pi}{b} x\right) \sin \left(\frac{(2m+1)\pi}{a} y\right) \int_{a}^{b} e^{-ik\sin \alpha x'} \sin \frac{(2n+1)\pi}{b} x' dx' \int_{0}^{a} e^{-ik\sin \beta y'} \sin \frac{(2m+1)\pi}{a} y' dy'.
\]

Assume that the angle between \( \vec{k}_2 \) and \( x \) axis (\( y \) axis) is \( \vec{\tilde{\zeta}} - \alpha (\vec{\tilde{\zeta}} - \beta) \), and \( \alpha(\beta) \) is the angle between \( \vec{k}_2 \) and the surface of \( yz (xz) \), then we have

\[
k_{2x} = k \sin \alpha, \quad k_{2y} = k \sin \beta,
\]

\[
\vec{n} \cdot \vec{k}_2 = k \cos \theta,
\]

where \( \theta \) is the angle between \( \vec{k}_2 \) and \( z \) axis. Substituting Eq. (32) and (33) into (31) gives

\[
\Phi_j(x, y, z; t) = -\frac{e^{ikR}}{4\pi R} e^{-i\omega t} \sum_{j=x,y,z} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{16A_j}{(2m+1)(2n+1)^2 \pi^2} e^{i \sqrt{\frac{4\pi^2}{\lambda^2} - \left(\frac{2m+1}{b} \pi\right)^2} c'} \sin \left(\frac{(2n+1)\pi}{b} x\right) \sin \left(\frac{(2m+1)\pi}{a} y\right) \int_{0}^{b} e^{-ik\sin \alpha x'} \sin \frac{(2n+1)\pi}{b} x' dx' \int_{0}^{a} e^{-ik\sin \beta y'} \sin \frac{(2m+1)\pi}{a} y' dy'.
\]

Substituting Eq. (34) into (28), one can get

\[
\Phi(x, y, z; t) = -\frac{e^{ikR}}{4\pi R} e^{-i\omega t} \sum_{j=x,y,z} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{16A_j}{(2m+1)(2n+1)^2 \pi^2} e^{i \sqrt{\frac{4\pi^2}{\lambda^2} - \left(\frac{2m+1}{b} \pi\right)^2} c'} \sin \left(\frac{(2n+1)\pi}{b} x\right) \sin \left(\frac{(2m+1)\pi}{a} y\right) \int_{0}^{b} e^{-ik\sin \alpha x'} \sin \frac{(2n+1)\pi}{b} x' dx' \int_{0}^{a} e^{-ik\sin \beta y'} \sin \frac{(2m+1)\pi}{a} y' dy'.
\]

Eq. (35) is the total diffraction wave function in the diffraction area. From the wave function, we can obtain the diffraction intensity \( I \) on the display screen, we have

\[
I \propto |\Phi(x, y, z; t)|^2.
\]

4. Double-slit diffraction wave function of photon

From Eq. (23), in the first slit, the photon wave function \( \psi_1(x, y, z; t) \) is

\[
\psi_1(x, y, z; t) = \sum_{j=x,y,z} \sum_{m=0}^{\infty} \frac{16A_j}{(2m+1)(2n+1)^2 \pi^2} \sin \left(\frac{(2n+1)\pi x}{b}\right) \sin \left(\frac{(2m+1)\pi y}{a}\right) e^{i \sqrt{\frac{4\pi^2}{\lambda^2} - \left(\frac{2m+1}{b} \pi\right)^2} c'} \sin \left(\frac{(2n+1)\pi}{b} x\right) \sin \left(\frac{(2m+1)\pi}{a} y\right) \int_{0}^{b} e^{-ik\sin \alpha x'} \sin \frac{(2n+1)\pi}{b} x' dx' \int_{0}^{a} e^{-ik\sin \beta y'} \sin \frac{(2m+1)\pi}{a} y' dy'.
\]
The total diffraction wave function for the double-slit is
\[ \Phi(x, y, z; t) = c_1 \Phi_1(x, y, z; t) + c_2 \Phi_2(x, y, z; t), \]
where \(|c_1|^2 + |c_2|^2 = 1\). From Eq. (42), we can obtain the counts \(C\) in the detectors \(D_1\) or \(D_2\) is
\[ C \propto |\Phi(x, y, z; t)|^2. \]
In the experiment of two-photon interference [18], The 458 nm line of an Argon Ion laser is used to pump a 5mm BBO ($\beta$-BaB$_2$O$_4$) crystal, which is cut for degenerate collinear type-II phase matching to produce pairs of orthogonally polarized signal and idler photons. Each pair emerges from the crystal collinearly, with $\omega_s \approx \omega_i \approx \omega_p/2$, where $\omega_j$ ($j = s, i, p$) are the frequencies of the signal, idler and pump, respectively. The signal and idler are interfered by the same double-slit experiment device, and the interference-diffraction pattern of signal and idler photons are separated by the beam splitter PBS and are detected by the photon counting detectors $D_1$ and $D_2$, respectively. The output pulses of each detector are sent to a coincidence counting circuit for the signal-idler joint detection. The experiment setup is shown in FIG. 3 of Ref. [18].

Since the wavelength of signal and idler photons are equal, and the double-slit experiment device are same, their interference-diffraction wave function are same, i.e., Eq. (42). The counts of photon counting detectors $D_1$ and $D_2$ are directly proportional to $|\Phi(x, y, z; t)|^2$, and the counts of photon coincidence counting detectors $D$ is directly proportional to $|\Phi(x, y, z; t) \cdot \Phi(x, y, z; t)|^2$. In the following, we shall compare the theory result with the experiment data.

5. Numerical result

The double-slit interference-diffraction experiment of two-photon had been reported by Milena D’Angelo in Ref. [18]. The experiment parameters are: the wavelength of signal and idler photons are $\lambda_s = \lambda_i = 916nm$, the width of each slit is $a = 0.13mm$, the distance between the two slits is $d = 0.4mm$. In theory calculation, we take the wavelength, the slit width and the distance between the two slits are same as experiment values. In calculation, the theory parameters are taken as: $c_1 = 0.955, c_2 = 0.298, A_x = A_y = A_z = 0.896$, the slit length $b = 1.31 \times 10^{-2}$ and the slit thickness $c = 2.65 \times 10^{-5}$. In solid curve is our theoretical calculation, and the dot curve is the experiment data [18]. From FIG. 4, we find that the theoretical result is in accordance with the experiment data, when the diffraction angle $\beta$ is in the range of $|\beta| \leq 2(mrad)$. When the diffraction angle $\beta$ is in the range of $|\beta| \geq 2(mrad)$, the theoretical result has a small discrepancy with the experiment data. We think the experiment data should be measured accurately, and the theoretical calculation should be improved furtherly.

6. Conclusion

In conclusion, we study two-photon interference with the approach of photon quantum theory, and comparison the theoretical result with the experimental data. We find that the calculation result is in accordance with the experiment data, when the diffraction angle $\beta$ is in the range of $|\beta| \leq 2(mrad)$. When the diffraction angle $\beta$ is in the range of $|\beta| \geq 2(mrad)$, the theoretical result has a small discrepancy with the experiment data. We think the experiment data should be measured accurately, and the theoretical calculation should be improved furtherly.
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FIG. 4: Comparison between theoretical prediction from (43) (solid line) and experimental data taken from [18] (circle point).