

Article

Quantum Origin of Circular Aperture Diffraction: A Velocity-Perpendicular Force Mechanism for Wave–Particle Interaction

Chao-Fei Liu

School of Science, Jiangxi University of Science and Technology, Ganzhou 341000, China; liuchaofei@jxust.edu.cn

Abstract

Starting from the circular aperture diffraction experiment, this paper decomposes the intrinsic interactions underlying wave–particle duality and proposes a specific interaction force: the velocity-perpendicular interaction force. We derive the characterization formula of this force and show that it can induce the phenomenon of circular aperture diffraction of light, with the theoretical results being highly consistent with those calculated by the Huygens–Fresnel principle. The direction of this force is perpendicular to the relative velocity, originating from the coupling effect between the wave nature of light and the particle nature of the circular aperture structure, and it satisfies a modified inverse square law of distance related to the relative velocity. When photons pass through different positions of the circular aperture, the symmetry effect generates a net interaction time. The product of the main component of this force, the net interaction time, and the radius of the circular aperture constitutes a modulation quantity (a ratio of the Planck’s constant), which exerts an on–off modulation effect on the interaction force, thereby inducing the emergence of annular diffraction fringes. This study provides a novel physical interpretation for the circular aperture diffraction of light from the perspective of interaction forces and clarifies the possible existence form of wave–matter interaction forces. This force formula is expected to effectively describe the behavior of microscopic particles, just like the Schrödinger equation, while providing a brand-new perspective on interactions. It holds great application prospects in fields such as single-photon manipulation and quantum precision measurement.

Keywords: the velocity-perpendicular interaction force; circular-aperture diffraction; photon; quantum mechanics



Received: 13 April 2026

Revised: 30 June 2026

Accepted: 1 July 2026

Published: 2 July 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Circular aperture diffraction is conventionally explained within the framework of the Huygens–Fresnel principle [1–7]. According to this principle, every point on a propagating wavefront acts as a source of secondary wavelets, whose mutual superposition on an observation screen gives rise to the observed diffraction pattern. In the case of circular aperture diffraction, secondary spherical waves emanate from all points of the wavefront transmitted through the aperture, and their coherent superposition produces the characteristic pattern of alternating bright and dark rings.

Although light manifests particle-like properties under certain conditions, circular aperture diffraction predominantly reveals its wave nature. Descriptions based on wave optics therefore provide a quantitatively accurate and widely accepted account of this

phenomenon. Moreover, circular aperture diffraction serves as important experimental evidence supporting the wave nature of light in quantum mechanics, reinforcing the established concept of wave–particle duality.

Nearly all studies on circular aperture diffraction have basically inherited the main ideas of the Huygens–Fresnel principle [8–10], Rayleigh–Sommerfeld diffraction integral [11,12], or modern electromagnetic theory [13–20]. At their foundation, all these approaches rely on the superposition of waves. This naturally raises a fundamental question: can diffraction be understood outside the paradigm of wave superposition? Are there alternative physical mechanisms capable of explaining circular aperture diffraction? An affirmative answer would significantly advance our understanding of the fundamental nature and dynamical behavior of light.

Single-photon detection experiments, such as which-path experiments [21–25], provide direct experimental evidence for the momentum change caused by the interaction between photons and gratings. In particular, which-path experiments clearly confirm that measuring the propagation path of a photon inevitably disturbs its momentum state, thereby destroying interference and diffraction patterns. This clearly reveals the inherent physical connection between wave–particle complementarity and momentum transfer. Especially in recent years, by trapping single atoms in the quantum ground state using optical tweezers, Ref. [26] has successfully realized the “recoiling slit” thought experiment proposed by Einstein in 1927, which intuitively verifies that photons produce a tiny momentum recoil effect when passing through a movable slit. On the basis of the above single-photon detection experiments, this study intends to propose a novel interpretive framework based on the interaction forces generated by the wave–particle duality, so as to provide new research perspectives and approaches for further investigating the physical mechanism of circular aperture diffraction.

The circular aperture possesses perfect axial symmetry. A photon passing precisely through the center along the normal direction should experience no directional deflection due to symmetry. However, a photon incident normally but offset from the aperture center should undergo a deflection oriented along the radial direction of its entry point.

Given the intrinsic wave–particle duality of matter, particularly for photons, it is physically reasonable to assume that diffraction arises from an interaction between the aperture and the photon. During this process, the photon’s propagation direction changes, implying a corresponding change in its momentum. How should this momentum transfer be understood microscopically? Is momentum still conserved? To resolve these questions, we propose an explanation based on an interaction force perpendicular to the photon’s velocity.

The organization of this paper is as follows: In Section 2, based on circular aperture diffraction, we first introduce the hypothesis of the velocity-perpendicular interaction force and derive its possible formation. Section 3 analyzes the effective interaction time of this force within the aperture region. In Section 4, we derive a modified wavelength associated with the momentum change in photons during their interaction with the aperture. In Section 5, we explore the characteristics of the modulation function that modulates photons during the circular aperture. Section 6 provides a comprehensive description of the force characteristics for normally incident photons. In Section 7, we present the angular deflection and resulting pattern predicted by the velocity-perpendicular force hypothesis. Section 8 examines the dependence of fringe number on the adjustable parameter k . Section 9 explores in detail the effect of individual force components affecting fringe formation. Section 10 conducts a quantitative comparative analysis between the results derived from the proposed theory and the classical theory. Section 11 serves as the discussion part of this paper, which illustrates the unique advantages of the proposed model, reveals the physical origin of each coefficient, and verifies the consistency between

the model, existing experimental results and fundamental quantum mechanical principles. Section 12 presents the research prospects, putting forward three potential research topics in view of the limitations of the current model. Finally, Section 13 summarizes the core research conclusions of this study.

2. Theory of Velocity-Perpendicular Interaction Force

Matter exhibits wave–particle duality. Based on this fundamental property, we propose the following hypothesis: the particle nature and wave nature of matter can be treated separately, and we analyze the interaction between a circular aperture and a photon as a specific case study. We assume that there exists an interaction between the particle nature (or wave nature) of the circular aperture and the particle nature (or wave nature) of the photon. Meanwhile, there is also a cross-interaction between the particle nature (or wave nature) of the circular aperture and the wave nature (or particle nature) of the photon.

How, then, do such interactions produce mechanical effects? It is well known that the magnitude of universal gravitation is proportional to the product of the masses of two objects and inversely proportional to the square of the distance between them. Similarly, the magnitude of Coulomb force is proportional to the product of the electric charges of two objects and inversely proportional to the square of the distance between them. Drawing on this general law, we take the characteristic of being inversely proportional to the square of distance as an important reference when investigating the interaction force between a photon and a circular aperture. This raises the question: what is the origin of such an inverse square force? Evidently, this force no longer originates from the mass or electric charge of objects, but should instead be attributed to the relative velocity between the photon and the circular aperture.

Why is relative velocity the source of the interaction force? Essentially, the form of existence of matter is inseparable from motion, and motion is an inherent property of matter. When the relative velocity between the photon and the circular aperture is zero—that is, when there is no relative motion—their relative displacement remains constant, and no dynamic interaction effect can arise. Only when relative velocity exists does their relative displacement change over time. This variation in displacement constitutes the core prerequisite for deriving velocity, acceleration, and interaction forces; beyond this, there are no other identifiable physical factors between the two from which interaction forces can be explicitly derived.

Further consideration: if such an interaction generates a special force that does work on the photon, would it cause the photon’s velocity to increase and thus violate the fundamental law of the constancy of the speed of light? The answer is clearly negative. We may reasonably hypothesize that the direction of this special force is perpendicular to the direction of the relative velocity between the photon and the circular aperture. According to mechanical principles, when the direction of a force is perpendicular to the direction of an object’s motion, the force does no work and only changes the object’s direction of motion—an effect consistent with the characteristic role of centripetal force in circular motion. Through this hypothesis, potential contradictions such as non-conservation of momentum, non-conservation of energy, and non-constancy of the speed of light can be completely avoided, ensuring the self-consistency of the hypothesis.

Therefore, we can simply write the above force as

$$F_{J1/2} \sim \frac{u}{r^2}$$

where $J = M, w$. M denotes matter and w denotes wave.

In the dimensions, we find that

$$F_{J1J2} \cong h \frac{u}{r^2}$$

h is Planck's constant. The Planck's constant is not only a fundamental constant in quantum mechanics, but also a core element that links the microscopic and macroscopic worlds and reveals the essence of quantum phenomenon. Here, we find that the correlation coefficient of this assumed force, which is directly proportional to the relative velocity and inversely proportional to the square of the distance, can actually be Planck's constant.

Now, we continue to consider the circular aperture, whose configuration has the highest degree of symmetry. Suppose the radius of the circular aperture is R , and the origin of coordinates is at the center of the circular aperture. Obviously, we cannot simply use $F_{J1J2} \cong h \frac{u}{r^2}$ to represent the force acting on the photon when it passes through a certain position in the circular aperture. The force is related to the distance from the boundary of the circular aperture. Therefore, let us assume

$$F_{J1J2} \cong h \frac{u}{(g_{J1J2} + R - r)^2}$$

g_{J1J2} is a correction constant. When photons pass perpendicularly through the circular aperture's boundary, the interaction force cannot be infinite. Therefore, we add this correction constant.

Next, we will explore in detail the possible characteristics of each term of F_{J1J2} . First, let us explore F_{M1M2} . Obviously, it can be initially expressed as

$$F_{M1M2} = C_{M1M2} * h \frac{u}{(g_{M1M2} + R - r)^2} \quad (1)$$

C_{M1M2} is the corresponding constant.

Secondly, we consider F_{w1w2} , which describes the interaction force between the wave nature of the circular aperture and that of the photon. It is obvious that the fluctuation frequency of the circular aperture should be very large, far greater than that of the normal photon. It is very likely that within one period of the photon, the wave of the circular aperture has gone through multiple periods. So, in addition to considering the interaction part similar to Formula (1), we should consider a random modulation term. Therefore, F_{w1w2} can be written as

$$F_{w1w2} = C_{w1w2} * h \frac{u}{(g_{w1w2} + R - r)^2} * Random \quad (2)$$

Random is a random number in the interval $[0, 1]$. C_{w1w2} is the coupling constant between the fluctuation of waves.

We assume that F_{M1w2} describes the interaction force between the particle nature of the circular aperture and the wave nature of the photon. Waves are periodic. We might as well add a modulation function $Y(r) = (1 - \cos^{2N_1}(2\pi Q(r)))^{2N_2}$, where N_1 and N_2 are integers and are used to control the modulation. Obviously, the value of the modulation function is $0 \leq Y(r) \leq 1$. When $N_1 = 0$ ($N_2 > 0$), we have $Y(r) \equiv 0$. When $N_2 = 0$ ($N_1 > 0$), we have $Y(r) \equiv 1$.

$Q(r)$ is something that is modulated during the interaction between photons and circular apertures. What can be used for modulation in this process? That is the force in

this interaction process, and the time of this process, and the spatial radius R of this process. Apart from this, there is nothing else that can be used for modulation. So, we get

$$\begin{cases} Q(r) \sim h \frac{u}{(g_{M1w2} + R - r)^2} \\ Q(r) \sim t(r) \end{cases}$$

Therefore, we can assume

$$Q(r) = Q_0 \frac{u}{(g_{M1w2} + R - r)^2} * t(r) + Q_1 \quad (3)$$

Q_0 is a constant and Q_1 is a dimensionless constant, symbolizing a phase change to the $Y(r)$ function.

Now, the interaction force can be written as

$$F_{M1w2} = C_{M1w2} * h \frac{u}{(g_{M1w2} + R - r)^2} * Y(r) \quad (4)$$

Similarly, F_{w1M2} describes the interaction force between the wave nature of the circular aperture and the particle nature of the photon. Although the frequency of the circular aperture's fluctuation is very fast, its periodicity still exists. We write this interaction force to be

$$F_{w1M2} = C_{w1M2} * h \frac{u}{(g_{w1M2} + R - r)^2} * Y(r)$$

In the above assumptions, even if one of them is not appropriate, we can avoid the error by modulating the relative intensity parameters such as C_{w1M2} and C_{M1w2} to zero.

For simplicity, we assume that the position correction constants in the above interaction forces are $g_{M1M2} = g_{w1w2} = g_{M1w2} = g_{w1M2} = g_0$. In addition, both F_{M1w2} and F_{w1M2} are particle-wave interaction forces, and we classify them into one term. So, we will obtain

$$\begin{cases} F_{M1M2} \rightarrow F_M = C_M * h \frac{u}{(g_0 + R - r)^2} \\ F_{w1w2} \rightarrow F_w = C_w * h \frac{u}{(g_0 + R - r)^2} * Random \\ F_{M1w2}, F_{w1M2} \rightarrow F_{Mw} = C_{Mw} * h \frac{u}{(g_0 + R - r)^2} * Y(r) \end{cases}$$

Now, the total interaction force we have obtained is

$$F_{\perp u} = F_M + F_w + F_{Mw} = \frac{hu}{(g_0 + R - r)^2} * (C_M + C_w * Random + C_{Mw} * Y(r)) \quad (5)$$

From the above formulas, we can see that on the basis of the inverse ratio law of the square of the distance, the correction term g_0 of the distance is introduced. What factors might it be related to? First of all, this item must be related to the diameter $2R$ of the circular aperture. Secondly, it must also be related to the wavelength of photons. Here, we introduce a corrected wavelength λ_g , and assume

$$g_0 = \sqrt{2R * \lambda_g} \quad (6)$$

Here, we do not directly use the wavelength λ of the photon, but instead employ a corrected wavelength λ_g that has a significant relationship with the wavelength of the photon. The main reason is that we cannot directly determine at present that $\sqrt{2R * \lambda}$ is the appropriate correction constant. Based on the actual characteristics of circular aperture diffraction, we will present the possible and specific forms of the corrected wavelength λ_g in the following text.

Now, we obtain

$$F_{\perp u} = F_M + F_w + F_{Mw} = \frac{hu}{(\sqrt{2R * \lambda_g} + R - r)^2} * (C_M + C_w * Random + C_{Mw} * Y(r)) \quad (7)$$

3. The Effective Interaction Time of the Net Interaction Force

Although we have assumed the interaction force between the circular aperture and the photon. However, the prerequisite is that this force is perpendicular to the direction of the photon's movement. And it should exist in all directions of the vertical plane. Its resultant force should be zero. It seems that the forces should not cause a deflection of the photon's movement direction.

Herein, we need to consider the duration during which the interaction force is exerted between the photon and the boundary of the circular aperture. If one can get the onset time and termination time of the force, as well as find its effective duration of action, the product of this force and its effective duration would yield an impulse perpendicular to the direction of motion. This impulse would be the fundamental cause of the diffraction of photons.

Figure 1 shows a schematic diagram of a photon that passes through a circular aperture. The radius of the circular aperture is R , and the photon is incident perpendicularly at the position r away from the center of the circular aperture. The thickness of the circular aperture is d . If the thickness of the circular aperture increases, will it result in a longer interaction time? The answer is no. Current experiments show that thicker circular apertures do not cause a stronger diffraction.

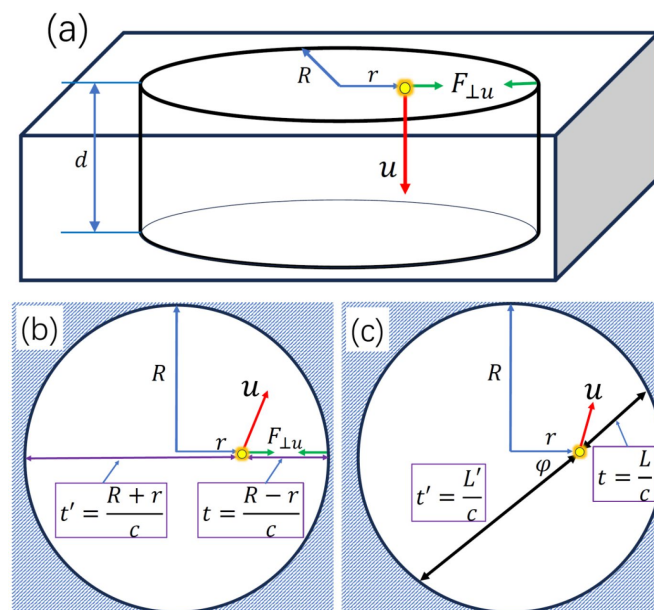


Figure 1. Schematic diagram of acting time of the net interaction force of photons passing perpendicularly through a circular aperture. (a) The photon at position r passes through the circular aperture. (b) The time when a photon interacts with the circular aperture's wall along the diameter. (c) The time when a photon interacts with the circular aperture's wall of any angle.

Suppose that the photon is subjected to an interaction force at the position r in the circular aperture. The time when this force occurs should be related to the distance from the photon to the boundary of the circular aperture. Suppose at the time of $t = \frac{R-r}{c}$, there is an interaction force $F_{\perp u}$ being generated between the photon and the right wall of the circular aperture. However, the left wall of the circular aperture has not yet felt interaction

force at this time. The time when the photon interacts with the left wall of the circular aperture is $t' = \frac{R+r}{c}$. So, within the time of $\Delta t = t' - t = \frac{2r}{c}$, the photon only experiences a unilateral interaction force with the right wall. Starting from the time of $t' = \frac{R+r}{c}$, the resultant force acting on the photon perpendicular to its direction of motion is zero.

In other words, the distance between a photon and different positions on the circular aperture varies. The time required for the force to be generated is equal to the distance divided by the speed of light. Therefore, along the line passing through the aperture's diameter, the distance difference reaches its maximum value, which also results in the maximum time difference in the interaction force.

According to Figure 1c, we have $r * \sin \varphi = \sqrt{R^2 - \left(\frac{L+L'}{2}\right)^2}$ and $2r * \cos \varphi = L' - L$, where $L' = \sqrt{R^2 - (r * \sin \varphi)^2} + r * \cos \varphi$ and $L = \sqrt{R^2 - (r * \sin \varphi)^2} - r * \cos \varphi$. For a fixed position r , the time difference is

$$\Delta t = t' - t = \frac{2r * \cos \varphi}{c} \quad (8)$$

Only when $\varphi = 0$, we have the maximum time difference of $\frac{2r}{c}$. Meanwhile, we have the minimum distance $L = R - r$ from the photon to the boundary of the circular aperture.

4. Characteristics of Modulated Wavelengths

During the effective interaction time, how much has the momentum of the photon changed due to the interaction between the circular aperture and the photon? Here, we represent the changed momentum with Δp , which can be written as $\Delta p = F_{\perp u} * \Delta t$. Obviously, $\frac{\Delta p}{p}$ is the deflection angle of the photon.

Therefore, we obtain the deflection angle

$$\Delta \theta = 2 * \arcsin \left(\frac{\frac{\Delta p}{2}}{p} \right) = 2 * \arcsin \left(\frac{F_{\perp u} * \Delta t}{2p} \right) = 2 * \arcsin \left(\frac{F_{\perp u} * \frac{r}{h/\lambda}}{h/\lambda} \right)$$

and

$$\sin \frac{\Delta \theta}{2} = \frac{\lambda r}{(g_0 + R - r)^2} * (C_M + C_w * \text{Random} + C_{Mw} * Y(r)) \quad (9)$$

When the photon passes through the exact center of the circular aperture, the effective time of the interaction between the photon and the circular aperture is $\Delta t = 0$. And at this time, the deflection angle is constantly 0.

When R is very large, we know that the half-angle width of the Airy spot of circular aperture diffraction is $\Delta \phi = 1.22 \frac{\lambda}{2R}$. We assume that the photon at the boundary of the circular aperture can precisely diffract to this angle, that is, $\Delta \phi = 1.22 \frac{\lambda}{2R} = (\Delta \theta)_{\max}$. Therefore, we can obtain

$$\sin \left(\frac{\Delta \theta}{2} \right)_{\max} = \frac{\lambda R}{(g_0 + R - R)^2} * (C_M + C_w * \text{Random} + C_{Mw} * Y(r)) \leq \frac{\lambda R}{g_0^2} * (C_M + C_w + C_{Mw})$$

When $\left(\frac{\Delta \theta}{2} \right)_{\max}$ is very small, we have $\sin \left(\frac{\Delta \theta}{2} \right)_{\max} = \left(\frac{\Delta \theta}{2} \right)_{\max}$. And we obtain

$$(\Delta \theta)_{\max} = 1.22 \frac{\lambda}{2R} \leq 2 \frac{\lambda R}{g_0^2} * (C_M + C_w + C_{Mw})$$

So, g_0 should satisfy

$$g_0 = \sqrt{2R * \lambda_g} \leq \sqrt{(2R)^2 * \frac{(C_M + C_w + C_{Mw})}{1.22}}$$

We can assume that $C_g = C_M + C_w + C_{Mw} = 1$.

When the diffraction angle of the circular aperture is almost the half-width of the Airy spot, the circular aperture should be very large. Then, we have $\lambda_g \rightarrow \frac{2R}{1.22}$. Obviously, when the radius of the circular aperture is large, the corrected wavelength λ_g is also very large. So, according to $\lambda_g \rightarrow \frac{2R}{1.22}$, we know that the corrected wavelength λ_g cannot exceed the diameter of the circular aperture, that is, $\lim_{R \rightarrow \infty} \lambda_g \rightarrow 2R$.

Now, let us continue to explore the possible characteristics of the corrected wavelength λ_g . First of all, it should be a function related to the wavelength and the diameter of the circular aperture. Secondly, the corrected wavelength λ_g itself is a correction of wavelength λ , and its prerequisite is the interaction between photons and the circular aperture. In addition, when the circular aperture is very close to the wavelength directly, the corrected wavelength λ_g should also be very close to the wavelength, that is, $\lim_{R \rightarrow \lambda/2} \lambda_g = \lambda$. Furthermore, let us assume there is a dust particle or an air molecule with a very small diameter, which is disk-shaped and can precisely fill the void in the circular aperture. According to symmetry, the circular aperture should have very similar diffraction properties to the disk. In fact, when light passes through the air and encounters many air molecules, its diffraction is also very weak. Therefore, when the diameter of the circular aperture is very small, its diffraction should be very weak and similar to that of air molecules, that is, $\lim_{R \rightarrow 0} \frac{\lambda}{\lambda_g} \sim 0$. Similarly, the corrected wavelength λ_g should also be much greater than the wavelength of the photon, that is, $\lim_{R \rightarrow 0} \lambda_g \gg \lambda$.

Based on the above analysis, we find that the corrected wavelength λ_g can be written as a function

$$\lambda_g = \left(1 + \frac{\lambda}{k * 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{2R + k^2\lambda} \quad (10)$$

k is a regulating constant. Equation (10) can simultaneously meet the requirements of photons mentioned above in various situations. For instance,

$$\begin{cases} \lim_{R \rightarrow \infty} \left(1 + \frac{\lambda}{k * 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{2R + k^2\lambda} = 2R \\ \lim_{R \rightarrow \lambda/2} \left(1 + \frac{\lambda}{k * 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{2R + k^2\lambda} = \left(1 + \frac{1}{k}\right) \frac{\lambda^2 + (k\lambda)^2}{\lambda + k^2\lambda} \rightarrow \lambda \\ \lim_{R \rightarrow 0} \left(1 + \frac{\lambda}{k * 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{2R + k^2\lambda} = \left(1 + \frac{\lambda}{k * 2R}\right) \lambda \gg \lambda \end{cases} \quad (11)$$

Figure 2 shows the variation in the corrected wavelength λ_g with the radius of the circular aperture. When $R/\lambda \gg 1$, the growth of λ_g almost linearly increases with the increase in the circular aperture radius R [see Figure 2a], and its growth trend is almost parallel to the line of $2R/\lambda$, which is linear. The larger the value of k is, the slower the growth of λ_g becomes as the radius R of the circular aperture increases. Theoretically, when the value of k is infinite, λ_g will approach λ . Figure 2b is a corresponding enlarged plot. At smaller scales, the value of the corrected wavelength λ_g is almost close to the photon wavelength λ , especially when the value of k is relatively large. Figure 2c shows the value of the corrected wavelength λ_g when the radius of the circular aperture is less than the wavelength λ . In this region, the smaller the radius is, the greater the value of the corrected wavelength λ_g would be.

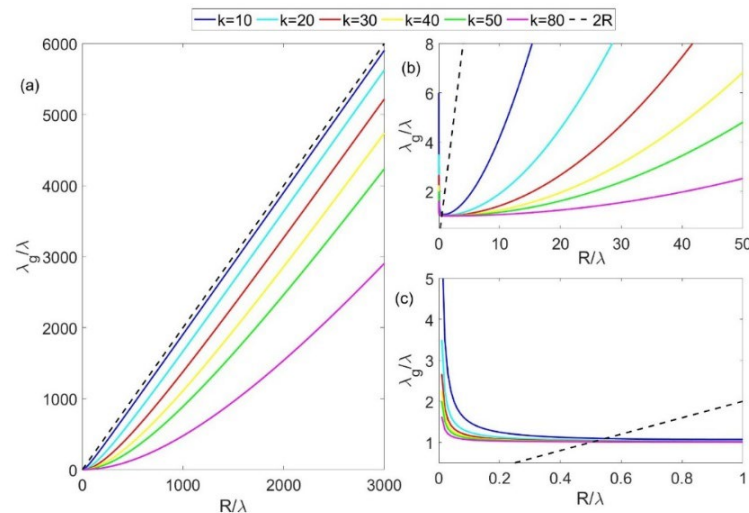


Figure 2. The corrected wavelength λ_g with the variation in radius of the circular aperture. **(a)** The variation in the corrected wavelength λ_g with the radius of the circular aperture under various modulation parameters k . **(b)** The result of a smaller radius of the circular aperture. This figure is an enlarged view of Figure (a). **(c)** The corrected wavelength λ_g when the radius of the circular aperture is less than the wavelength. The black dotted line represents the linear variation line of $2R/\lambda$.

5. Modulation Function

In our theory, the velocity-perpendicular interaction force is inversely proportional to the square of the distance. It indicates that the farther away from the boundary of the circular aperture, the smaller the force acts. If the force can lead to the appearance of diffraction fringes, it must be necessarily related to the modulation function $Y(r) = (1 - \cos^{2N_1}(2\pi Q(r)))^{2N_2}$. If $Y(r) = 0$, it indicates that the photon will not be subject to the interaction of the force at all. Especially when C_M and C_w also tend to 0, the photon will not be affected in any way and will not deflect. This case can only correspond to the dark fringes in the diffraction. It is obvious that when $Y(r)$ varies between $[0, 1]$, the position where dark fringes appear should be the area where the modulation of the particle-wave interaction force is extremely small. So, when dark fringes appear, we have

$$(1 - \cos^{2N_1}(2\pi Q(r)))^{2N_2} = 0$$

Therefore, we have

$$2\pi Q(r_n) = n\pi \quad (12)$$

$$Q_0 h \frac{u}{(g_0 + R - r_n)^2} * t(r_n) + Q_1 = Q_0 h \frac{u}{(g_0 + R - r_n)^2} * \frac{2r_n}{u} + Q_1 = \frac{n}{2} \quad (13)$$

At the position of the first dark fringe, we have

$$Q_0 h \frac{2r_1}{(g_0 + R - r_1)^2} + Q_1 = \frac{1}{2}$$

Theoretically, the deflection angle of photon at the position of r_1 should be $1.22 \frac{\lambda}{2R}$, that is

$$\frac{h \frac{u}{(g_0 + R - r_1)^2} * t(r_1)}{h/\lambda} = \frac{h \frac{u}{(g_0 + R - r_1)^2} * \frac{2r_1}{u}}{h/\lambda} = \frac{2r_1 \lambda}{(g_0 + R - r_1)^2} = 1.22 \frac{\lambda}{2R}$$

In addition, the width of the fringes of circular aperture diffraction is generally $d' = S \frac{\lambda}{2R}$. That is, along the center of the diffraction pattern outward, the half-angle width of the n th dark fringe is approximately

$$\Delta\theta_n \cong 1.22 \frac{\lambda}{2R} + (n-1) \frac{\lambda}{2R}$$

Namely,

$$\frac{h \frac{u}{(g_0 + R - r_n)^2} * \frac{2r_n}{u}}{h/\lambda} = \frac{2r_n \lambda}{(g_0 + R - r_n)^2} = 1.22 \frac{\lambda}{2R} + (n-1) \frac{\lambda}{2R}$$

and

$$Q_0 h \frac{u}{(g_0 + R - r_n)^2} * \frac{2r_n}{u} + Q_1 = Q_0 h \frac{2r_n}{(g_0 + R - r_n)^2} + Q_1 = \frac{n}{2}$$

We eliminate $\frac{2r_n}{(g_0 + R - r_n)^2}$ and get

$$Q_0 h \left[1.22 \frac{\lambda}{2R} + (n-1) \frac{\lambda}{2R} \right] = \left(\frac{n}{2} - Q_1 \right) \lambda$$

By combining the above two formulas, we obtain $Q_0 h * n \frac{1}{2R} = \frac{n}{2}$ and $Q_0 h * 0.22 * \frac{1}{2R} = -Q_1$. So, we can continue to get $Q_0 = \frac{R}{h}$ and $Q_1 = -0.11$.

Therefore, we eventually obtain $Q(r) = R \frac{2r_n}{(g_0 + R - r_n)^2} - 0.11$. Its normal formation can be written as

$$Q(r) = \frac{2R}{2h} * \frac{hu}{(\sqrt{2R * \lambda_g} + R - r)^2} * t(r) - 0.11 = R \frac{2r}{(g_0 + R - r)^2} - 0.11 \quad (14)$$

Figure 3 shows the properties of the modulation quantity $Q(r)$ and the modulation function $Y(r)$. We have considered circular apertures of various radius and the value of k for corrected wavelengths. Figures 3(a1), 3(b1), 3(c1) and 3(d1) show $Q(r)$ of $R = 5\lambda$, $R = 20\lambda$, $R = 100\lambda$, and $R = 500\lambda$, respectively. The modulation quantity $Q(r)$ always has a larger value as it gets closer to the boundary of the circular aperture. At the position r of the circular aperture with the same radius, the larger the value of k is, the greater the modulation quantity $Q(r)$ is. When the radius is very small, the variation in the modulation quantity $Q(r)$ at various k values is also very small [see Figure 3(a1)]. Figure 3(b1) shows the modulation quantity $Q(r)$ with the greatest variation in its value range. For example, the values of the green curve ranges from 0 to 10. When the radius increases to $R = 100\lambda$, the range of the modulation quantity $Q(r)$ becomes smaller instead [see Figure 3(c1)]. For example, the green curve has a value range of 0 to 5 now. If the radius of the circular aperture is further increased to $R = 500\lambda$, the range of the modulation quantity $Q(r)$ will be further reduced [see Figure 3(d1)].

The modulation function $Y(r)$ varies between 0 and 1. And the closer it is to the boundary of the circular aperture, the higher the variation frequency is. Figure 3(a2) shows that when the radius is very small, the modulation function $Y(r)$ takes almost the same value at different k values, especially in the area near the center of the circular aperture. Figure 3(b2) shows that the wider the range of values of the modulation quantity $Q(r)$, the more periods the modulation function $Y(r)$ has. Figure 3(c2) shows that the number of variation periods of the modulation function $Y(r)$ has decreased. The main reason is that when the radius of the circular aperture increases, the value range of the modulation quantity $Q(r)$ becomes smaller. Figure 3(d2) shows that for a very large circular

aperture radius, the number of variation periods of the modulation function $Y(r)$ is actually very small.

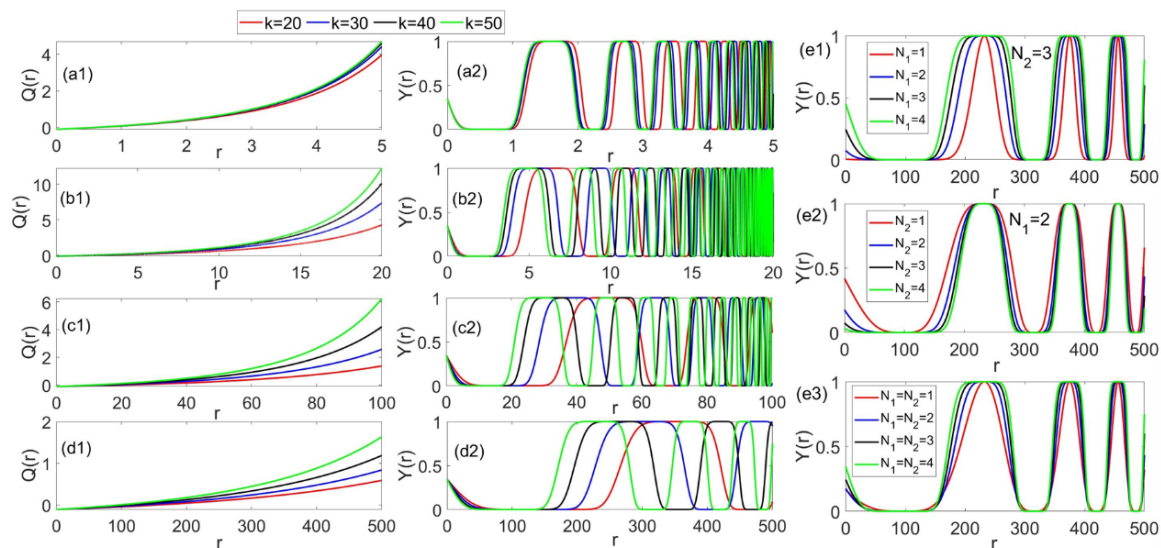


Figure 3. Modulation quantity $Q(r)$ and modulation function $Y(r)$. We set $N_1 = N_2 = 4$. (a1–d1) $Q(r)$ of various radius of circular aperture, where (a1) $R = 5\lambda$, (b1) $R = 20\lambda$, (c1) $R = 100\lambda$, (d1) $R = 500\lambda$. (a2–d2) are the values of the corresponding modulation function $Y(r)$. (e1–e3) The modulation function $Y(r)$ under the regulation of N_1 and N_2 . We set the parameters $k = 50$ and $R = 500\lambda$. (e1) The effect of N_1 on the variation in the modulation function $Y(r)$ at different positions of the circular aperture. N_2 is fixed at 3. (e2) The effect of N_2 on the variation in the modulation function $Y(r)$ at different positions of the circular aperture. N_1 is fixed at 2. (e3) The effect of N_1 and N_2 increasing simultaneously on the variation of the modulation function $Y(r)$. The unit of length is λ .

In Figure 3(e1–e3), we further examine the properties of the modulation function $Y(r)$ under the regulation of N_1 and N_2 . We firstly fix $N_2 = 3$ and increase N_1 . The increasing of N_1 can lead to a wider area where $Y(r)$ is approximately 1 and a narrower area where $Y(r)$ is 0 within each modulation period [see Figure 3(e1)]. Then, we fix $N_1 = 2$ and change N_2 . The increase in N_2 can cause the region where $Y(r)$ is approximately 0 to widen and the region where $Y(r)$ is approximately 1 to slightly narrow within each modulation cycle [see Figure 3(e2)]. When N_1 and N_2 increase synchronously, the areas approximately equal to 0 and 1 increase synchronously too. While the intermediate change area decreases [see Figure 3(e3)].

6. Characteristics of Forces as Photons Passing Perpendicularly Through the Circular Aperture

Figure 4 shows the forces acting on photons at different positions of the circular aperture. First, we examine the forces on photons when the radius of the circular aperture is $R = 5\lambda$. The closer to the boundary of the circular aperture, the greater the interaction force F_M is, which is monotonically varying [see the blue curve in Figure 4a]. The closer to the boundary of the circular aperture, the greater the range of the random interaction force F_w is [see the green curve in Figure 4a]. In addition, the particle–wave interaction force F_{Mw} varies periodically, exhibiting local maximum and minimum values. The closer it is to the boundary of the circular aperture, the larger its amplitude and the shorter its period [see the black curve in Figure 4a]. The red curve in Figure 4a represents the resultant force of the above three forces.

Figure 4b shows the results that the radius of the circular aperture is $R = 20\lambda$. Compared with the corresponding forces in Figure 4a, the amplitude of the force in Figure 4b

is much smaller than that in Figure 4a. However, the number of variation cycles of F_{Mw} is greater. When we increase the radius of the circular aperture to $R = 100\lambda$, we obtain less cycle-modulated F_{Mw} and smaller magnitudes of each force [see Figure 4c]. Compared with Figure 4b, although the radius has increased, the number of cycles in Figure 4c is reduced instead. If the radius of the circular aperture is further increased to $R = 500\lambda$ [see Figure 4d], the cycle-modulated force can still be observed, with only a very small number of cycles remaining.

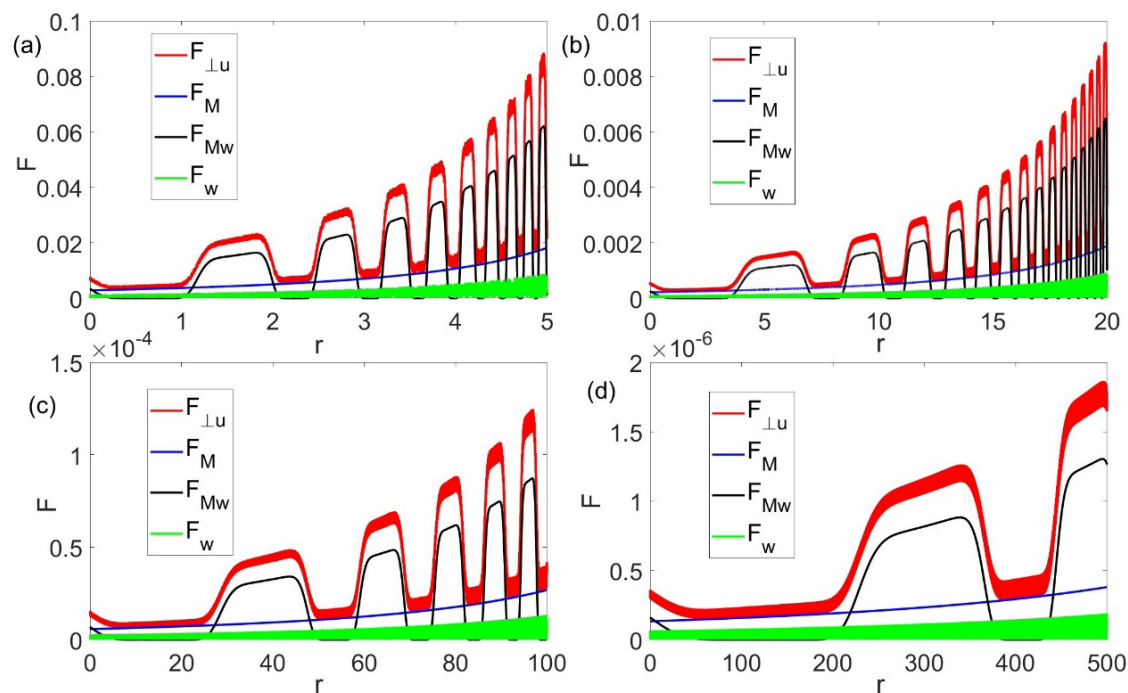


Figure 4. Forces on photon at different positions of the circular aperture. (a) The radius R of the circular aperture is $R = 5\lambda$. (b) $R = 20\lambda$. (c) $R = 100\lambda$. (d) $R = 500\lambda$. We take $C_M = 0.2$, $C_w = 0.1$ and $C_{Mw} = 0.7$. In addition, we set $k = 30$, and $N_1 = N_2 = 4$. The unit of forces is $\frac{hc}{\lambda^2}$ and the unit of length is λ .

The circular aperture is essentially a two-dimensional (2D) structure. Figure 5 further investigates the distribution characteristics of the velocity-perpendicular force experienced by photons when passing through this 2D circular aperture. This section only presents the distribution of the magnitude of the force and temporarily does not discuss its direction. Subsequent discussions will confirm that only F_{Mw} is the core factor inducing the appearance of fringes, while the other interaction forces are non-dominant factors. Based on this, this study selects the parameter combination $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$ for subsequent analysis.

Figure 5a,b,d show the distribution of the total velocity-perpendicular interaction force on photons when the circular aperture radius is $R = 5\lambda$, 20λ , and 500λ , respectively. The results clearly indicate that the force distribution exhibits a distinct multi-concentric ring structure; specifically, along the radial direction outward, the force values corresponding to the rings gradually increase, while the ring width narrows accordingly. It is worth noting that the circular aperture radius exerts a significant modulation effect on the number of rings: for a large-scale circular aperture [Figure 5d], the number of rings is the smallest instead.

To further analyze the above characteristics, we take the circular aperture with $R = 100\lambda$ as an example for separate discussion. Figure 5(c1) shows the particle–particle interaction force F_M . Due to the existence of the geometric boundary of the circular aper-

ture, this force has its maximum value at the boundary and the minimum at the center, forming a bowl-shaped distribution. Figure 5(c2) shows the particle–wave interaction F_{Mw} , which presents a multi-ring structure concentric with the circular hole under the circular aperture configuration, with the number of rings becoming denser as the radius increases. Figure 5(c3) shows the wave–wave random interaction force F_w , whose amplitude distribution also features the maximum at the boundary and the minimum at the center. Figure 5(c4) shows the total interaction force $F_{\perp u}$, which overall exhibits a concentric ring distribution. The closer it is to the boundary of the circular aperture, the smaller the spacing between the rings, a characteristic that exhibits high consistency under different circular aperture scales.

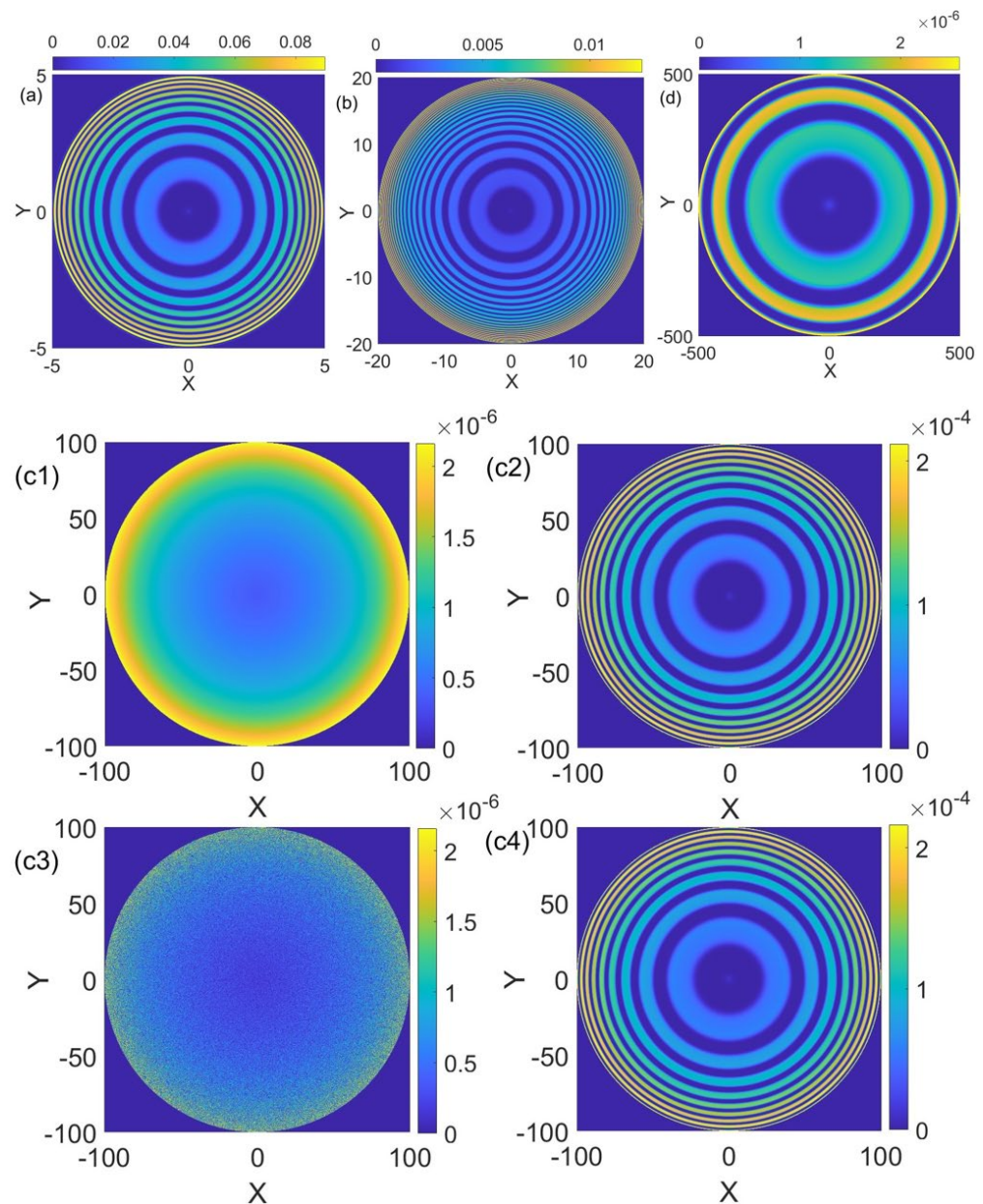


Figure 5. The magnitude of the force acting on a photon when it passes perpendicularly through a circular aperture. (a) The velocity-perpendicular interaction force $F_{\perp u}$ on photons in the circular aperture with radius $R = 5\lambda$. (b) $F_{\perp u}$ on photons where $R = 20\lambda$. (d) $F_{\perp u}$ on photons where $R = 500\lambda$. (c1–c4) The results where $R = 100\lambda$. (c1) Particle–particle interaction force F_M . (c2) Particle–wave interaction force F_{Mw} . (c3) Wave–wave interaction force F_w . (c4) The total velocity-perpendicular force $F_{\perp u}$. We take $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$. In addition, we set $k = 40$, $N_1 = N_2 = 4$. The unit of forces is $\frac{hc}{\lambda^2}$ and the unit of length is λ .

7. The Deflection Angle and Pattern of Photons Passing Through Circular Aperture

Figure 6 shows the distribution of the deflection angle of photons passing through the circular aperture under the velocity-dependent interaction force model, where the radii of the circular aperture are 5λ , 20λ , 100λ , and 500λ , respectively. The results indicate that the photon deflection angle also forms a multi-concentric ring structure, a feature highly similar to the force distribution shown in Figure 5. Specifically, the radial outward deflection angle gradually increases while the width of the rings narrows accordingly, with the rings becoming denser near the boundary. In terms of the number of rings, Figure 6b ($R = 20\lambda$) exhibits the most, and Figure 6d ($R = 500\lambda$) has the least. A comparison reveals that Figure 6a,c are quite similar in pattern morphology and total number of rings, yet the range of deflection angle values in the former is nearly 20 times larger than that in the latter, demonstrating that the circular aperture size exerts a significant modulation effect on the deflection intensity.

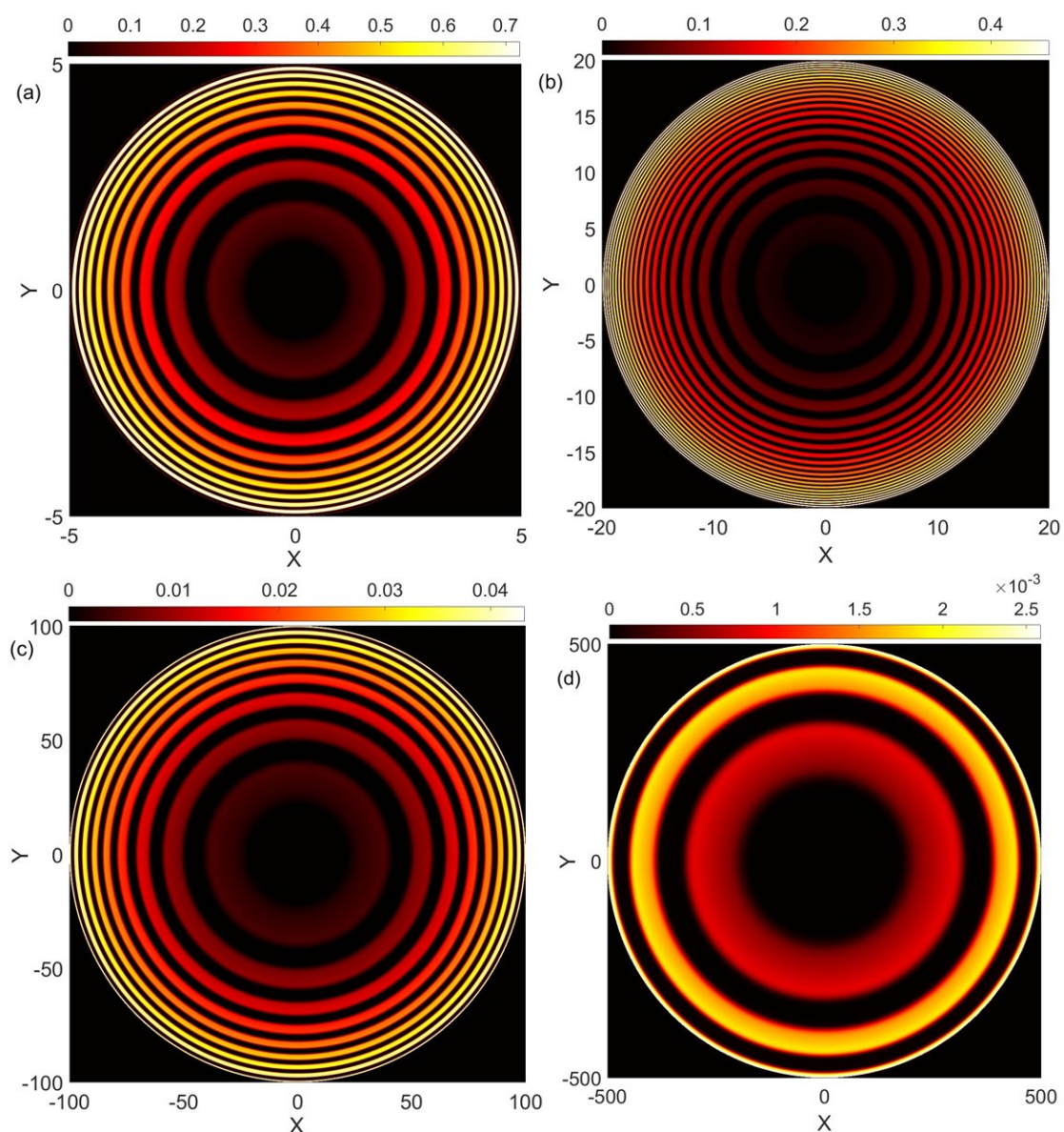


Figure 6. Deflection angles of photons passing perpendicularly through circular apertures of various scales. (a) $R = 5\lambda$. (b) $R = 20\lambda$. (c) $R = 100\lambda$. (d) $R = 500\lambda$. We adopt $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$. In addition, $k = 40$ and $N_1 = N_2 = 4$. The unit of length is λ .

Based on the above derivation, can the interaction force and the resulting deflection angle of light truly form the pattern of circular aperture diffraction? In Figure 7, we present the pattern formed by photons under the aforementioned interaction force, where the distance between the screen and the circular aperture is set to 5 m, and the photon wavelength is 589.3 nm. Figures 7a, 7b, 7c and 7d correspond to the cases where the radii of the circular hole are 5λ , 20λ , 100λ , and 500λ , respectively. From the simulation results, the photons exhibit a distinct distribution of alternating bright and dark rings on the screen. Among them, the cyan dashed circular ring represents the theoretical position of the dark fringe calculated based on the traditional circular aperture diffraction theory. Except for a slightly larger size of the central bright spot, the spacing between the formed rings is basically equidistant. Furthermore, the size of the central bright spot based on the photon distribution obtained from the theoretical simulation in this paper is highly consistent with the result calculated according to the Fresnel principle, which further verifies the rationality of the theory.

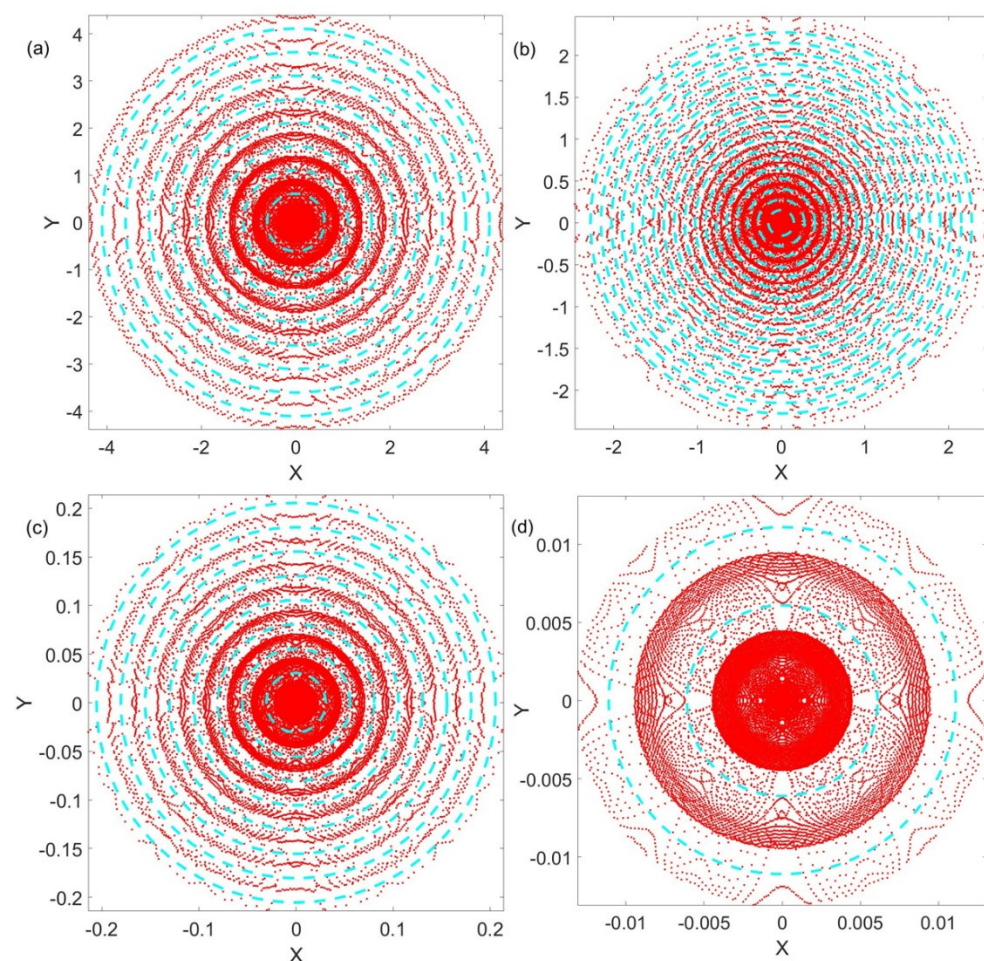


Figure 7. Patterns formed on a screen located 5 m behind the circular aperture after photons pass perpendicularly through circular apertures of various scales. (a) $R = 5\lambda$. (b) $R = 20\lambda$. (c) $R = 100\lambda$. (d) $R = 500\lambda$. We adopt $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$. In addition, $k = 40$ and $N_1 = N_2 = 4$. The wavelength $\lambda = 589.3 \times 10^{-9}$ m. The cyan ring marks the position of the dark ring of the corresponding circular aperture diffraction calculated by Huygens–Fresnel principle. The unit of length is the meter.

Under the above four cases of circular aperture radii, the number of diffraction rings appearing in Figure 7b is the largest, while that in Figure 7d is the smallest. This phenomenon indicates that the number of diffraction rings does not depend on the large scale of the circular hole. On the contrary, when the size of the circular aperture is too large,

the diffraction phenomenon will become indistinct, and it will be difficult to observe clear diffraction rings. Only when the circular aperture is within an appropriate size range can a large number of clearly distinguishable diffraction rings be formed. The overall morphology of the diffraction patterns in Figure 7a,c is extremely similar. However, a further comparison of the sizes of the diffraction rings reveals that the size of the diffraction rings in Figure 7a is approximately 20 times that in Figure 7c. This difference has a clear corresponding relationship with the variation rule of the circular aperture radius.

Figure 8 shows the intensity distribution of photons on a screen located 5 m away after passing through circular aperture of different scales. This is exactly the image we would observe on the screen in an experiment. They indeed form multiple concentric ring structures. Except for the central bright spot, the spacing between the bright rings is almost equidistant. The central bright spot has the maximum brightness, and the brightness of the bright rings decreases as we move outward. These characteristics are all consistent with traditional theory and real experiments. In addition, we use cyan circles to mark the positions of the dark fringes of circular aperture diffraction, calculated by the traditional theory (Huygens–Fresnel principle), for the corresponding circular aperture radii. We can observe that the velocity-perpendicular interaction force proposed in this work causes the photons to deflect upon entering the circular aperture, and their far-field pattern is in perfect agreement with the diffraction results obtained from the Huygens–Fresnel principle.

Figure 8(a2–d2) present the cross-sectional views of the intensity distributions shown in Figure 8(a1–d1). For comparison, we also provide the corresponding calculation results derived from the classical theory, namely the Huygens–Fresnel principle (see the blue curves). Whether it is the moderate aperture ($R = 20\lambda$) with numerous fringes, as shown in Figure 8(b1,b2) or the very large aperture ($R = 500\lambda$) where the ring structure is barely visible, as shown in Figure 8(d1,d2), the positions of the dark fringes predicted by traditional diffraction theory are in complete agreement with our theoretical results. Furthermore, Figure 8(a1,c1) are very similar, with the only difference being the scale of the pattern. Moreover, the size of the central bright spot corresponds to the position of the minimum angular half-width obtained from the Huygens–Fresnel principle [see Figure 8(a2–d2)]. We can see that the majority of the light is concentrated at the center of the annular pattern. We do indeed observe local maxima and minima in the intensity distribution, with the intensity significantly lower than that of the central bright spot. Furthermore, the positions of the intensity minima are in perfect alignment with the theoretical positions derived from the Huygens–Fresnel principle.

Furthermore, as can be seen from Figure 8(a2–c2), the background brightness at the local minimum positions (dark fringes) increases as we move closer to the central bright spot. Visually, this even creates the impression that some of the lower-order dark and bright rings seem to merge with the central bright spot, forming a centrally located bright spot with a larger apparent scale [see Figure 8(b1,b2)]. This result presents a fundamental distinction from the ideal scenario predicted by the Huygens–Fresnel principle, where the background brightness tends to zero at the positions of the dark rings. However, it shows a much higher degree of consistency with the non-ideal diffraction spot morphologies that are commonly observed in real experiments. This indicates that our theoretical results better reflect the actual physical phenomena.

Notably, combining the results from Figure 5 (force distribution), Figure 6 (deflection angle distribution), and Figures 7 and 8 (diffraction patterns), under the same parameter system, there exists a strict one-to-one correspondence between the concentric ring structures in each figure. Specifically, a certain radial ring zone in Figure 5a corresponds to a ring zone with an identical position in Figures 6a, 7a and 8(a1), respectively. This correspondence clearly reveals that the spatial modulation of the velocity-perpendicular

interaction force experienced by photons directly determines their deflection angle distribution, and ultimately modulates the structure of the far-field pattern. This finding establishes a direct causal link between the microscopic interaction mechanism and the macroscopic diffraction phenomenon.

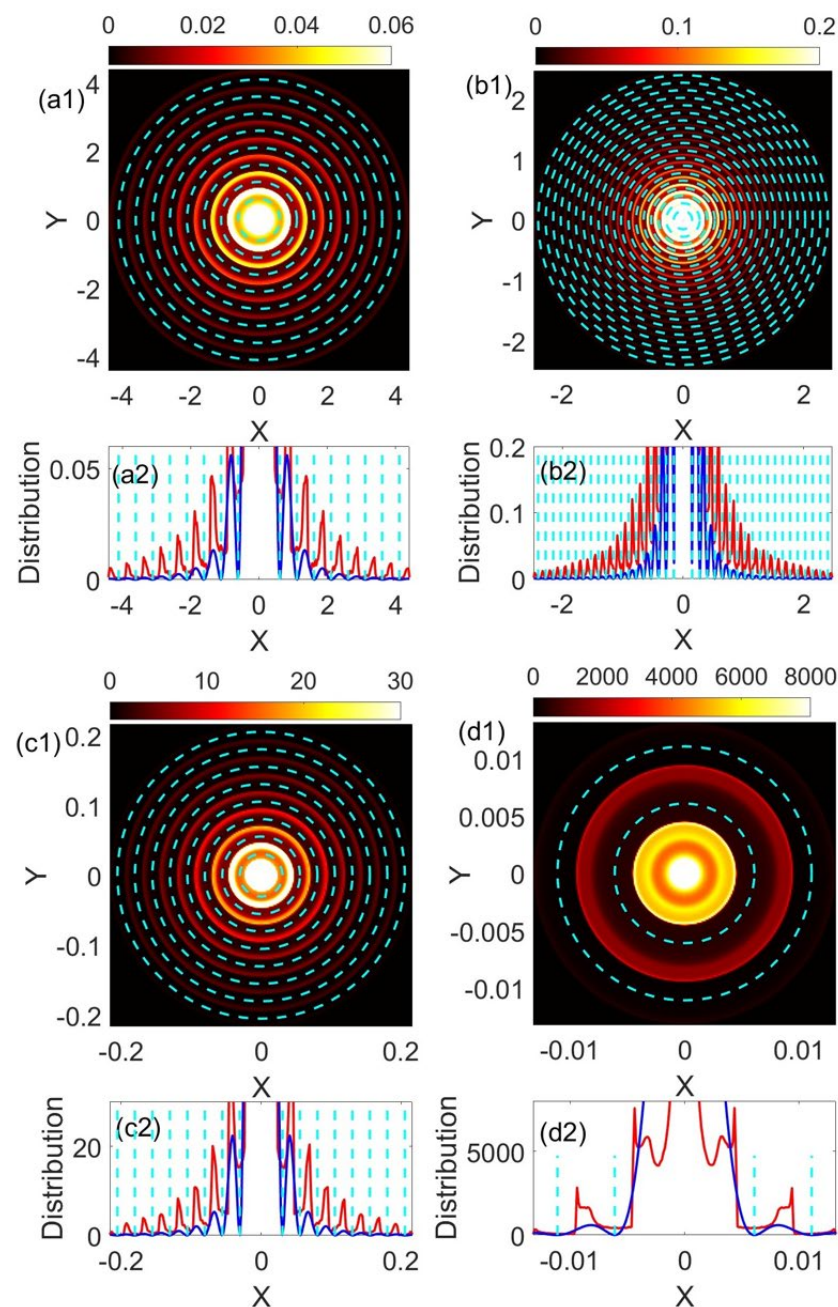


Figure 8. Intensity distribution of photons on the screen 5 m behind circular aperture after vertically passing through. **(a1)** The radius of the circular aperture is $R = 5\lambda$. **(b1)** The radius of the circular aperture is $R = 20\lambda$. **(c1)** The radius of the circular aperture is $R = 100\lambda$. **(d1)** The radius of the circular aperture is $R = 500\lambda$. The cyan dashed circular ring marks the theoretical position of the dark ring corresponding to the circular aperture diffraction at the given scale, calculated according to the Huygens–Fresnel principle. The red curves in panels **(a2–d2)** represent the enlarged cross-sectional profiles of the intensity distributions passing through the center in panels **(a1–d1)**. For comparison, the calculated results from classical theory are plotted as blue curves in each subpanel. The cyan line marks the theoretical position of the dark ring of circular aperture diffraction at the corresponding scale. We adopt $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$. In addition, $k = 40$ and $N_1 = N_2 = 4$. The photon wavelength we use is 589.3 nm. The unit of length is the meter.

8. Number of Fringes and the Parameter k

Since our simulation of the velocity-perpendicular interaction force can accurately predict the appearance of diffraction fringes, then what factors are related to the number of fringes? We found that adjusting the parameter k can change the number of diffraction fringes.

The position of the dark fringes is

$$R \frac{2r_n}{(g_0 + R - r_n)^2} - 0.11 = \frac{n}{2}$$

We know that $r_n \leq R$, and

$$n \leq 2R \frac{2r_n}{(g_0 + R - r_n)^2}$$

The number of dark fringes must satisfy

$$n \leq 2R \frac{2R}{(g_0)^2} = \frac{2R}{\lambda_g} = \frac{2R}{\left(1 + \frac{\lambda}{k \cdot 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{(2R + k^2\lambda)}}$$

The maximum number of dark fringes is

$$(n)_{max} = \left\lceil \frac{2R}{\left(1 + \frac{\lambda}{k \cdot 2R}\right) * \frac{(2R)^2 + (k\lambda)^2}{(2R + k^2\lambda)}} \right\rceil \quad (15)$$

Figure 9 shows the maximum number of dark fringes that can theoretically be observed when we change the modulation parameter k and the circular apertures' radius. The larger the modulation parameter k is, the greater the maximum number of dark fringes will be [see Figure 9a].

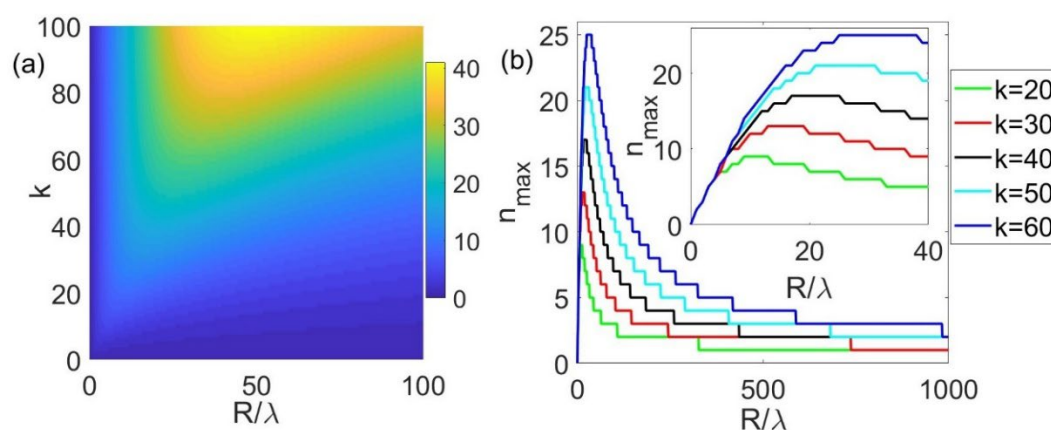


Figure 9. The theoretical maximum number of dark fringes. (a) The maximum number of dark fringes as function of the radius R and parameter k . (b) The variation in the maximum number of dark fringes with radius increasing.

In fact, the number of fringes is step-like as shown in Figure 9b. When the radius is very small, due to the size of the circular aperture, the number of stripes is relatively small. When the radius is very large, the diffraction ability of large-scale circular apertures is relatively weak. So, the number of fringes is also very small. In addition, the larger the parameter k is, the greater the maximum value of the dark fringes will be. When the radius R is very small ($R \rightarrow 0$), dark fringes will not be visible [see the insertion diagram

in Figure 9b]. Theoretically, if the value of k is infinite, we will obtain $\lambda_g \rightarrow \lambda$. Even if the radius of the circular aperture is very large, the number of fringes will also be very large. This is obviously somewhat inconsistent with the actual observation. In the above study, we estimated that the value of $k = 40$ would be relatively appropriate.

9. The Effect of Individual Force Components

In our model, we have assumed the existence of particle–particle interaction forces, wave–wave random interaction forces, and particle–wave interaction forces. When photons pass perpendicularly through the circular aperture, their diffraction would be the result of the combined effect of the above three interacting forces. In above text, we have mainly demonstrated the particle–wave interaction force. What roles do the other two forces play respectively in the process of photon diffraction? This is the topic we are going to discuss next. We can assume that during the diffraction process, only one of the interaction forces exists, while the other two are shielded. In this way, the diffraction results obtained from this single interaction force can fully reflect the essence of the force.

(1) The role of particle–particle interaction forces in the diffraction process

In the above text, we have found that it is necessary to ensure that $C_M + C_w + C_{Mw} = 1$. Here, we assume that $C_M = 1$, $C_w = C_{Mw} = 0$.

Figure 10 shows the results. Figure 10a shows the particle–particle interaction force F_M . The closer it is to the boundary of the circular aperture, the greater its value is. The magnitude of the deflection angle of the photons passing through the circular aperture caused by it is shown in Figure 10b. The diffraction pattern of the photon is shown in Figure 10c. It can be clearly observed that although photons diffract, the particle–particle interaction force F_M does not cause alternating bright and dark diffraction rings. Figure 10d further shows the cross-sectional view of the diffraction pattern. Indeed, no diffraction fringes appear. The two blue lines represent the boundary positions of the central bright spot in the theoretical Huygens–Fresnel principle.

(2) The role of wave–wave interaction forces in the diffraction process

Next, we will specifically examine the role of wave–wave random interaction forces in the diffraction process. Similarly, we take $C_w = 1$ and $C_M = C_{Mw} = 0$. In this way, we have $F_{\perp u} = F_w$, and the photon passing through the circular aperture will only be affected by the random interaction force F_w [see Figure 11a]. We find that the deflection angle caused by the random interaction force F_w , like the random force, is larger near the boundary of the circular aperture [see Figure 11b].

At the center of the circular aperture, the deflection angle is 0. Random forces cannot cause diffraction fringes either [see Figure 11c]. It merely causes a bright spot in the center. The further it spreads outward, the weaker the intensity of the light becomes. Figure 11d is a cross-sectional view through its center. Its center is very sharp, and it can be seen that the vast majority of the light is concentrated at the center position. And there are no fringes at all.

(3) The competition between particle–wave velocity-perpendicular interaction forces and the other two forces

In Figure 12, we only consider two of the three forces and ignore the other one. Figure 12a–c show the effects of the particle–wave interaction force F_{Mw} and the particle–particle interaction force F_M in diffraction. Obviously, diffraction fringes will appear [see Figure 12a]. Except for the central bright spot, the other bright rings are very weak [see Figure 12b]. Moreover, several tiny peaks appear on the bright ring, and the outer boundary is very steep [see Figure 12c]. These results show that the particle–particle interaction force F_M causes the central bright spot to become a superposition of multiple

bright rings during diffraction. This is quite different from the actual single-slit diffraction. Therefore, in the assumed velocity-perpendicular interaction force, the intensity of the particle–particle interaction force F_M should be much smaller than that of the particle–wave interaction force F_{Mw} .

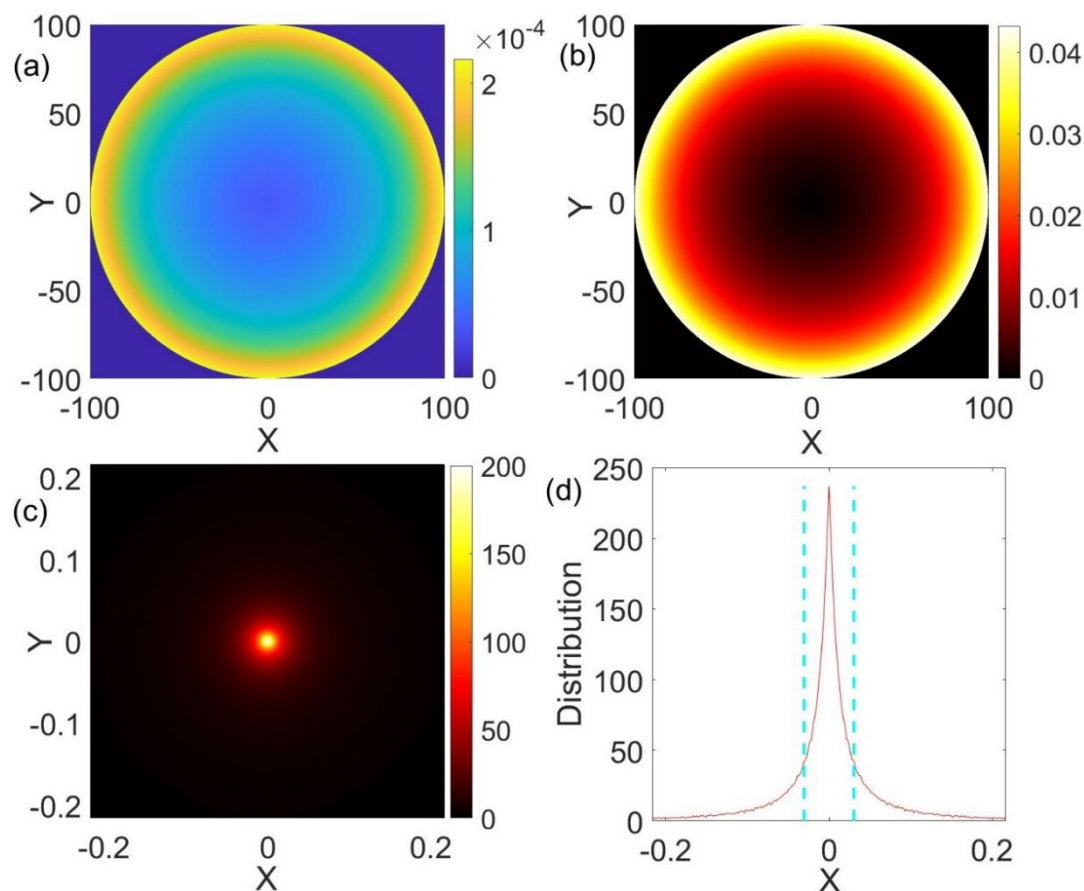


Figure 10. The role of particle–particle interaction force F_M in diffraction. (a) The particle–particle interaction force F_M . We take $C_M = 1$, $C_w = C_{Mw} = 0$, $k = 40$ and $N_1 = N_2 = 4$. The unit of force is $\frac{hc}{\lambda^2} = 5.73 \times 10^{-13}$ N. (b) The deflection angle caused by the single particle–particle interaction force F_M . (c) Diffraction pattern caused by the single particle–particle interaction force F_M . (d) Cross-sectional view of the diffraction pattern. The wavelength of the photons we use is 589.3 nm, and the radius of the circular aperture is $R = 100\lambda$. The screen is 5 m away from the circular aperture. The cyan line indicates the boundary position of the central bright spot determined by the Huygens–Fresnel principle. The unit of length is λ in (a,b). And the unit of length is meter in (c,d).

Figure 12d–f show the effects of the particle–wave interaction force F_{Mw} and the wave–wave random interaction force F_w in diffraction. Obviously, the diffraction fringes will also appear [see Figure 12d], with a very strong central bright spot and some very weak bright rings [see Figure 12e]. Moreover, the random interaction force causes the tiny peaks on the bright rings to disappear, and the outer boundary becomes flatter [see Figure 12f]. In addition, at the edges of the diffraction, the fringes become very indistinct. These results show that the wave–wave random interaction force F_w will reduce the peak value of bright fringes in diffraction. And it also reduces the recognizability of the fringes. Although our theory assumes this random interaction force, its proportion in diffraction should be very weak, or even negligible. The main part of velocity-perpendicular interaction forces should be the particle–wave interaction force F_{Mw} .

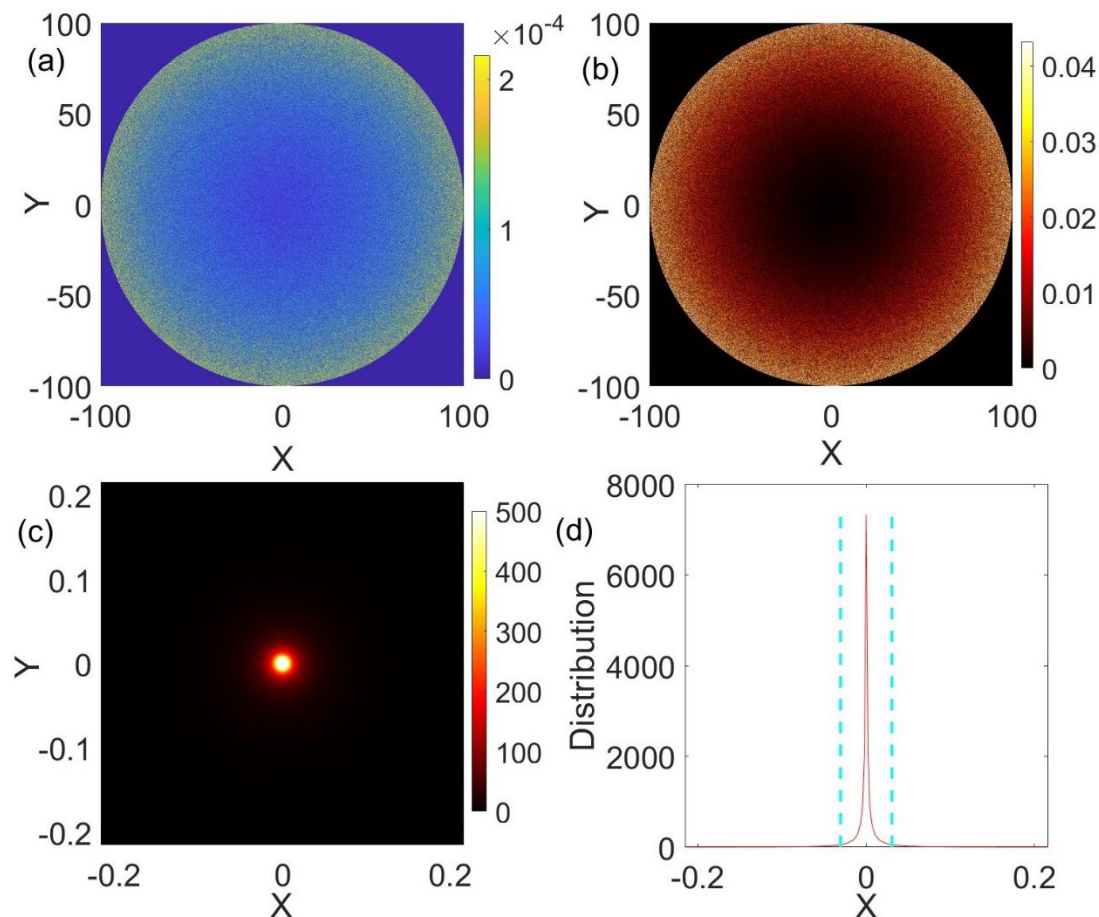


Figure 11. The role of wave–wave random interaction force F_w in diffraction. (a) Wave–wave random interaction force F_w . We take $C_w = 1$, $C_M = C_{Mw} = 0$, $k = 40$ and $N_1 = N_2 = 4$. The unit of forces is $\frac{hc}{\lambda^2} = 5.73 \times 10^{-13}$ N. (b) The deflection angle caused by the single wave–wave random interaction force F_w . (c) Diffraction pattern caused by the single wave–wave random interaction force F_w . (d) Cross-sectional view of the diffraction pattern. The wavelength of the photons we use is 589.3 nm, and the radius of the circular aperture is $R = 100\lambda$. The screen is 5 m away from the circular aperture. The cyan line indicates the boundary position of the central bright spot determined by the Huygens–Fresnel principle. The unit of length is λ in (a,b). And the unit of length is meter in (c,d).

For the combined effect of the particle–particle interaction force F_M and the wave–wave random interaction force F_w , they obviously cannot form diffraction fringes. Therefore, we do not present the corresponding results here.

It is possible to completely ignore the particle–particle interaction force F_M and the wave–wave random interaction force F_w . The particle–wave interaction force F_{Mw} is the key factor causing the diffraction phenomenon. Our initial interaction hypothesis deal with the wave nature and particle nature separately, and at least three kinds of forces would appear. Combined with the circular aperture diffraction phenomenon, only the particle–wave interaction force F_{Mw} is appropriate. Therefore, we can simplify the formula as

$$\begin{cases} F_{\perp u} = F_{Mw} = \frac{hu}{(\sqrt{2R*\lambda_g + R-r})^2} * Y(r) \\ Y(r) = (1 - \cos^{2N_1}(2\pi Q(r)))^{2N_2} \\ Q(r) = \frac{2R}{2h} * \frac{hu}{(\sqrt{2R*\lambda_g + R-r})^2} * t(r) - 0.11 \end{cases} \quad (16)$$

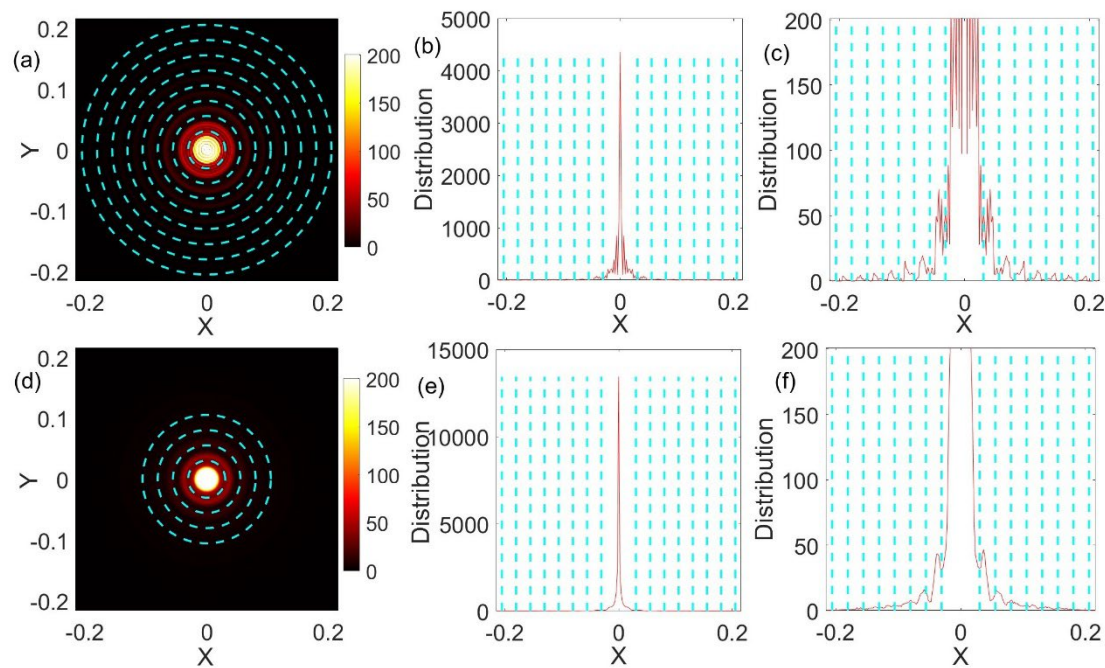


Figure 12. (a–c) The effects of the particle–wave interaction force F_{Mw} and the particle–particle interaction force F_M in diffraction. Here we set $C_{Mw} = 0.8$, $C_M = 0.2$ and $C_w = 0$. (a) Diffraction pattern. (b) Cross-sectional view of the diffraction pattern. (c) An enlarged view of the diffraction pattern. (d–f) represent the effects of the particle–wave interaction force F_{Mw} and the wave–wave random interaction force F_w in diffraction. Here we set $C_{Mw} = 0.8$, $C_w = 0.2$ and $C_M = 0$. (d) Diffraction pattern. (e) Cross-sectional view of the diffraction pattern. (f) An enlarged view of the diffraction pattern. The wavelength of the photons we use is 589.3 nm, and the radius of the circular aperture is $R = 100\lambda$. The screen is 5 m away from the circular aperture. In addition, we set $k = 40$ and $N_1 = N_2 = 4$. The cyan dashed circular rings or lines mark the theoretical position of the dark rings corresponding to the circular aperture diffraction at the given scale, calculated according to the Huygens–Fresnel principle. The unit of length is meter.

10. Quantitative Comparison with Results from Classical Theories

Subsequently, we conduct a benchmarking analysis between the predictions of the velocity-perpendicular interaction force theory and the results derived from classical theory (see Figure 13). Firstly, the numerical results presented in Figure 13(a1–c1) correspond one-to-one to those in Figure 8(a1). Figure 13(a1) quantifies the fractional light energy at different radial positions. To facilitate an intuitive theoretical benchmark comparison, blue curves are plotted to denote the calculations from classical theory, with the vertical axis of this subplot representing the logarithmic value of radial light energy fraction. The classical theoretical results exhibit multiple groups of wave peaks, whose amplitudes decay gradually as the radial distance from the central axis increases.

It should be noted that although classical theory predicts exactly zero light energy fraction at dark fringe positions, inherent numerical errors exist in simulation computations. Consequently, the radial light intensity does not approach negative infinity on the logarithmic coordinate scale. The decay trend of the theoretical curves proposed in this work is consistent with that of classical theory, with only a slightly slower amplitude decay rate. Meanwhile, dashed lines in the figure mark the locations of dark fringes, and the dark fringe positions predicted by our theory are basically in good agreement with those from classical theory.

Figure 13(b1) benchmarks the positions of all orders of dark fringes solved by the proposed model and classical theory. The vertical axis on the right side of this subplot denotes the relative error of dark fringe positions. Quantitative results reveal that the

maximum relative error of dark fringe positions of all orders predicted by our model against classical theory is less than 6%.

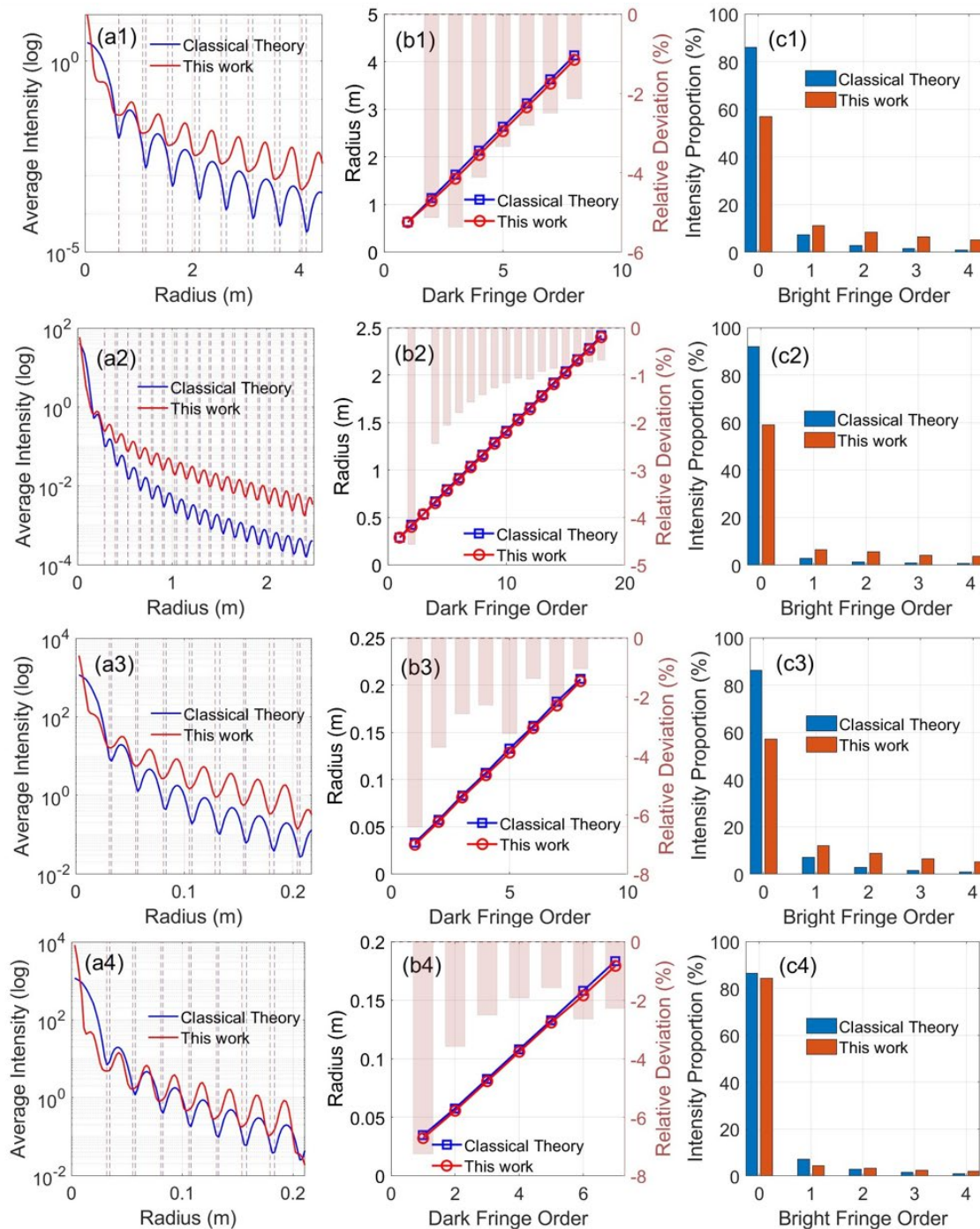


Figure 13. Quantitative comparison between the theoretical predictions of the velocity-perpendicular interaction force and the calculation results from classical theory. (a1–a4) The light intensity distributions at different radial positions under various cases. The total light energy for all cases is normalized to unity. Red and blue dashed lines denote the positions of dark fringes predicted by the corresponding theories. (b1–b4) The dark fringe positions corresponding to the results in (a1–a4); the vertical coordinate on the right denotes the relative error of dark fringe positions. (c1–c4) The light energy proportion of the central Airy disk and the first four bright fringes. We adopt $C_M = 0.01$, $C_w = 0.01$ and $C_{Mw} = 0.98$. In addition, $k = 40$. The wavelength $\lambda = 589.3 \times 10^{-9}$ m. (a1–c1) $R = 5\lambda$, $N_1 = N_2 = 4$. (a2–c2) $R = 20\lambda$, $N_1 = N_2 = 4$. (a3–c3) $R = 100\lambda$, $N_1 = N_2 = 4$. (a4–c4) $R = 100\lambda$, $N_1 = 4$, $N_2 = 4096$.

Figure 13(c1) further quantifies the fractional light energy contained in the central Airy disk and the first four bright fringes. The comparison demonstrates that the light energy fraction of the central Airy disk calculated by the present theory is lower, reaching approximately 70% of the value obtained from classical theory.

Figure 13(a2–c2) correspond to the results of the parameter sets shown in Figure 8(b1,b2), where a large number of diffraction fringes are produced. As indicated by Figure 13(a2), the predictions of the proposed theory agree excellently with classical theory, with particularly high consistency in dark fringe locations. According to the quantitative error data in Figure 13(b2), the maximum relative error of dark fringe positions is less than 5%. Figure 13(c2) presents the fractional light energy of the central Airy disk and the first four bright fringes under this parameter set. Compared with classical theory, the central Airy disk light energy fraction calculated by the present theory is lower.

Figure 13(a3–c3) correspond to the numerical results illustrated in Figure 8(c1,c2), for which the circular aperture radius is set as $R = 100\lambda$. Figure 13(a3) verifies that the overall predictions of the proposed theory are consistent with classical theory. Figure 13(b3) shows that the maximum relative error of dark fringe positions under this parameter set does not exceed 6%. Meanwhile, the data in Figure 13(c3) still reveal that the fractional light energy of the central Airy disk derived from our theory is smaller than that calculated via classical theory.

It should be noted that when the radius of the circular aperture is extremely large, only a small number of diffraction fringes can be observed. Then, the corresponding results cannot serve as valid references for comparative analysis. For this reason, no detailed quantitative comparison between the results in Figure 8(d1,d2) and classical theoretical predictions is carried out in this work.

To resolve the discrepancy in the fractional light energy of the Airy disk shown in Figure 13(c1–c3), supplementary verification calculations are performed with parameters $N_1 = 4$ and $N_2 = 4096$, which produce numerical results nearly identical to classical theory. For example, in Figure 13(a4), the curves obtained from the proposed model overlap closely with those from classical theory, and both exhibit essentially identical decay trends. Moreover, the dark fringe positions in Figure 13(b4) show excellent agreement with classical solutions, with the relative error kept below 8%. The fractional light energy of the Airy disk presented in Figure 13(c4) also matches the classical counterpart almost perfectly.

For the numerical validation shown in Figures 5–8, we set $N_1 = N_2 = 4$. This parameter combination was chosen randomly without deliberate parameter tuning to boost the model's fitting performance. All quantitative comparison data presented above collectively demonstrate that the theory proposed in this work possesses favorable overall reliability and delivers extremely high accuracy in calculating dark fringe positions.

Figure 14(a1,a2) further present the circular aperture diffraction patterns and their transverse cross-sectional profiles obtained with optimized coefficients, and these results correspond one-to-one to those in Figure 13(a4–c4). It can be seen that the simulation results derived from our theory show good overall agreement with the values predicted by the conventional theory, yet a non-zero background intensity still exists at the dark fringes.

In addition, Figure 14b systematically analyzes the dependence of the light energy fraction enclosed by the central Airy disk on parameter N_2 in the theoretical calculation proposed in this work. As illustrated in Figure 3 in the above text, parameter N_2 governs the variation rate of the modulation function over the interval from 0 to 1; a larger value of N_2 corresponds to a faster variation in the modulation function. According to Figure 14b, the light energy fraction of the Airy disk increases monotonically with the growth of N_2 and gradually converges to 1. Therefore, if the calculated light energy fraction of the

central Airy disk is lower than the theoretical value from conventional theory, parameter optimization can be realized by increasing the value of N_2 .

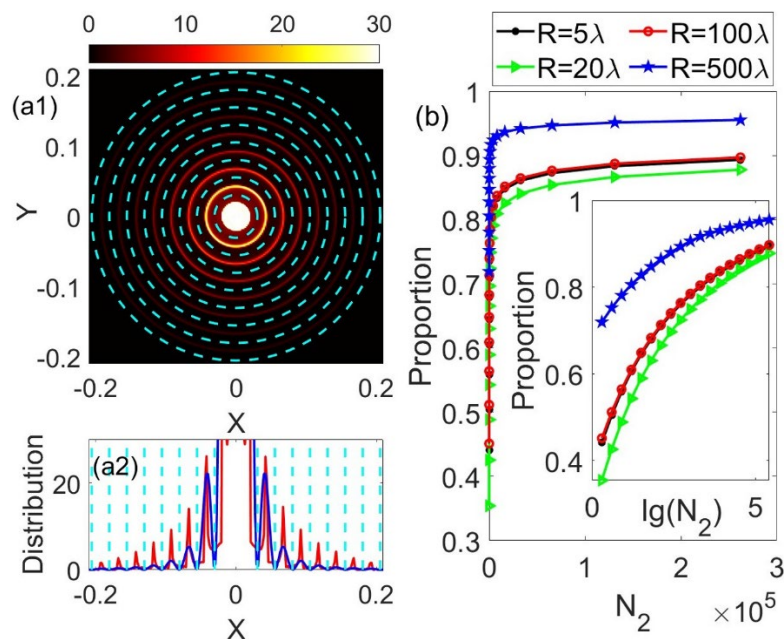


Figure 14. Circular aperture diffraction patterns under optimized parameters and the effect of parameter N_2 on the light energy fraction enclosed by the central Airy disk. (a1) Diffraction pattern with all parameters identical to those in Figure 13(a4); (a2) cross-sectional view passing through the center of the Airy disk, where red curve come from our theory and the blue curve represents the theoretical prediction from the Huygens–Fresnel theory. The cyan dashed circular rings or lines mark the theoretical position of the dark rings. (b) dependence of the light energy fraction of the Airy disk on parameter N_2 . All parameters are kept consistent with those in Figure 8 except for the variable N_2 . The inset presents results with the abscissa in logarithmic coordinates.

11. Discussion

(1) Some Properties of the Work

This work is built on the core hypothesis: there exists a novel interaction force that is always perpendicular to the relative velocity of particles. The force performs no work and merely alters the propagation direction of particles. The modulation parameter is defined as the ratio of the product of the force amplitude, system characteristic scale and net interaction time to Planck’s constant. It regulates the modulation function to realize the mutual transformation between wave-like and particle-like properties within the range from 0 to 1. On the basis of this hypothesis, we analyze the physical effects arising from the perpendicular interaction. Taking photon transmission through a circular aperture as the research subject, we verify that the proposed model can reproduce the results of standard circular aperture diffraction.

It is important to emphasize that the velocity-perpendicular interaction force hypothesized in this study is not derived from Maxwell’s equations, quantum optics, quantum electrodynamics (QED), or standard effective Hamiltonians. Neither does this work introduce conventional optical boundary mechanisms such as electromagnetic coupling interactions and condensed-matter quantum boundary effects. This constitutes the core counterintuitive novelty of the present research: unexpectedly, the results verify that the classical Airy disk diffraction pattern can be perfectly reproduced without relying on traditional classical electromagnetic or quantum theories.

Conversely, if the proposed model had been constructed upon well-established theoretical frameworks (e.g., electromagnetism or quantum theory) from the outset, this study

would merely amount to theoretical refinement or extended applications within existing paradigms. Reproducing circular aperture diffraction would then be a predictable outcome, and the work would possess no distinctive innovative value.

Overall, we have proposed a new theory of interaction forces and fully verified its validity through the circular aperture diffraction model. As the theory is rather unconventional, many readers may raise questions about it. For instance, why did this work choose circular aperture diffraction as an example? Optical diffraction also includes single-slit diffraction, grating diffraction, and so on. Is the formula proposed in this paper equally applicable to these cases?

The circular aperture exhibits high symmetry, which makes the interpretation of the velocity-perpendicular interaction force relatively concise and intuitive. Single-slit diffraction is also an excellent example for illustrating this interaction theory. We find that single-slit diffraction, double-slit interference, grating diffraction, and some other optical phenomena can also be quantitatively explained by the velocity-perpendicular interaction force theory. Due to the length limitations and the thematic focus of this paper, additional results are not presented in this work.

The key to the successful explanation of diffraction phenomena by this velocity-perpendicular interaction force theory lies in the introduction of Planck's constant, the proposal of the effective interaction time, and the definition of the modulation quantity. In this circular aperture diffraction model, the modulation quantity requires a constant offset of 0.11, which originates from the intrinsic requirement of the circular aperture system. For conventional single-slit diffraction, this constant correction term is not required at all.

Furthermore, the expression for this velocity-perpendicular interaction force is remarkably concise, involving only four physical parameters: the relative velocity, the photon wavelength, the scale of the circular aperture system, and the interaction distance. The introduction of the Planck's constant inherently places this formula within the framework of quantum mechanics. In particular, the modulation quantity, which is expressed as a ratio relative to the Planck's constant, further clearly indicates that this interaction force formula is a theoretical expression specifically constructed for quantum systems.

(2) Discussion on the Physical Origin of Each Parameter

Some readers may have numerous questions. For example, why is the modified wavelength λ_g defined in this theory? Its functional form is only constrained by several limiting conditions in the paper, without a full derivation from first principles. In addition, other parameters such as the tunable parameter k , phase constant $Q_1 = -0.11$, and exponents N_1 and N_2 appear to originate from empirical fitting. Could the parameters be calibrated using independent experimental data, and can the physical range of admissible values for each parameter be specified?

Here we provide the following explanations. First, we clarify that all coefficients adopted in this work have no direct correlation with the material properties of the circular aperture or the wavelength of incident photons. We define the modified wavelength λ_g in this paper, and the tunable parameter k is introduced specifically for λ_g . The introduction of the modified wavelength λ_g is not merely to benchmark the predictions of classical wave optics, but to achieve consistency with actual experimental observations.

It is entirely feasible for us to directly adopt the original wavelength λ , which corresponds to taking an extremely large value of k in the defining formula of the modified wavelength λ_g . Under this circumstance, consistent with classical theory, the number of bright/dark diffraction rings predicted by our model is approximately $[2R/\lambda]$, which matches the number of fringes predicted by classical wave theory. Nevertheless, diffraction fringes may be completely unobservable in experiments when the circular aperture possesses a large dimension. Classical wave theory attributes this phenomenon simply to an

extremely low photon probability density and vanishingly weak light intensity, rendering the fringes undetectable.

Herein, by defining the modified wavelength λ_g and selecting an appropriate value of k , we directly avoid this probabilistic interpretation inherent to classical theory. Undoubtedly, probabilistic descriptions contain intrinsic uncertainty; as long as probabilistic reasoning is adopted, interpretations inconsistent with experimental observations cannot be entirely eliminated.

Secondly, deriving and solving physical outcomes under limiting conditions represents a mainstream and rigorous research methodology in physics, which is fully reasonable. Nevertheless, the reliability of the derived conclusions relies on three prerequisites: the rationality of limiting assumptions, the applicable bounds of the model, and the self-consistency of the physical mechanism. Numerous well-established theories in physics adopt this research paradigm, such as the ideal gas model (where molecular volume approaches zero and intermolecular interactions are neglected), the geometric optics limit (where the wavelength tends to zero), adiabatic processes, and the absolute zero temperature limit.

The velocity-perpendicular interaction force proposed in this work corresponds to a brand-new hypothesis, which is not described by any existing well-established fundamental theories, including Maxwell's equations, the Schrödinger equation, the QED Lagrangian, relativistic mechanics, fundamental quantum commutation relations, and lattice quantum field theory. As the first researchers to propose and verify this hypothesis, we do not yet have a complete, mature first-principles theoretical framework for direct derivations. Accordingly, we can only deduce the plausible form of λ_g via analyzing results under fundamental limiting conditions.

In this work, the independent experimental data adopted to constrain the tunable parameter k are the measured numbers of bright rings in circular aperture diffraction patterns, which are used to calibrate its physically admissible range ($k \geq 30$). Meanwhile, the measured half-angular width of the Airy disk in circular aperture diffraction serves as the independent experimental basis for the phase constant $Q_1 = -0.11$.

As for the exponential parameters N_1 and N_2 , they govern the transition rate of the modulation function as it varies between 0 and 1. In Figure 13, we have shown that the dark fringe positions predicted by our model exhibit strong robustness with respect to the exponential parameters N_1 and N_2 . Accordingly, N_1 and N_2 can take arbitrary values as long as the modulation function varies within the interval $[0, 1]$. Based on the results in Figure 14, we recommend the ranges $1 \leq N_1 \leq 5$ and $N_2 \gg N_1$ for circular aperture diffraction simulations.

In addition, only one representative set of values for the parameters C_M , C_w and C_{Mw} (i.e., 0.01/0.01/0.98) is adopted in Figures 5–8, with the aim of intuitively presenting diffraction results consistent with physical laws to readers. Furthermore, Figures 10–12 systematically investigate how different combinations of C_M , C_w and C_{Mw} affect diffraction patterns. All non-standard parameter combinations tested in this section fail to match real experimental observations. It is worth noting that the parameter set (0.01/0.01/0.98) used in Figures 5–8 is not chosen arbitrarily. This set of values is summarized based on extensive numerical simulations and validations. The simulation results confirm that C_{Mw} should approach 1, while C_M and C_w exert negligible modulating effects on the final diffraction patterns. Overall, the proposed model exhibits universal applicability, with all coefficients independent of aperture material properties and incident photon wavelength.

(3) How This Work Aligns with Experimental Research and Quantum Theory

Recently, a series of experiments on “which-path” detection [21–26] have played an important role in examining core quantum mechanical issues such as the wave–particle duality of light, the mechanism of quantum measurement, and the complementarity principle.

Such experiments essentially measure the momentum change in a single photon during the interaction with a grating. The present theory is precisely based on momentum change in the single photon as the core mechanical characteristic, revealing the microscopic physical mechanism of circular aperture diffraction from a novel perspective of particle–wave interaction. It provides a reasonable explanation for the microscopic interaction picture missing in traditional diffraction theories, including the superposition principle of wave optics and the probabilistic interpretation of quantum mechanics. Naturally, experiments based on “which-path” detection [21–26] can be employed to verify the formula of the velocity-perpendicular interaction force proposed in this work.

It is not difficult to see that the present theory is not only applicable to problems related to “which-path” detection, but can also be naturally extended to massive microscopic particle systems, including the interference and diffraction phenomena of electrons [27,28], neutrons [29], atoms [30], and even large molecules [31]. Furthermore, the theory proposed in this paper can not only reproduce the core characteristics of circular aperture diffraction, but also predict the physical effect that cannot be well explained by conventional theories: the existence of non-zero background intensity at dark fringes. Traditional theories of interference and diffraction generally predict that the probability of photon appearance at dark fringe positions is strictly zero. In real experiments, however, non-negligible background intensity commonly exists in dark fringe regions [27–31], showing an obvious deviation from ideal theoretical predictions. In contrast, the present theory is more naturally consistent with experimentally observed results.

Photon diffraction essentially falls within the scope of quantum mechanics [9]. According to the Heisenberg uncertainty relation, the position and momentum of a particle cannot be precisely determined simultaneously, and an intrinsic constraint exists between their measurement processes. In this work, we have established a correspondence between the incident position of a photon and its outgoing deflection, which appears to conflict with the uncertainty relation and seem to contradict the fundamental principles of quantum mechanics. In fact, although the present theory provides deterministic and quantitative descriptions of physical quantities such as photon position and momentum, these results correspond to theoretical predicted values prior to the occurrence of quantum measurement. The quantum measurement process corresponds exactly to the microscopic interaction process described by the present theory. The measurement itself is realized through microscopic interaction forces, and this process naturally leads to changes in the momentum and position of the particle.

Herein, we conduct a quantitative analysis of the uncertainty principle based on the circular aperture diffraction process. The circular aperture serves as our measuring device, and the position of the n -th bright fringe of photons corresponds to our measurement outcome. A position variation Δx arises during the momentum change Δp . According to our theory, $\Delta p = F_{\perp u} \Delta t$. This time interval induces the position shift Δx , such that Δx scales with Δt ; we adopt the direct relation $\Delta x = u \Delta t$. Therefore,

$$\Delta x \Delta p = u \Delta t * \Delta p = u \frac{(\Delta p)^2}{F_{\perp u}}$$

According to the constraint of $Q(r)$ at the n -th dark fringe, we have: $R \frac{2r_n}{(g_0 + R - r_n)^2} - 0.11 = \frac{n}{2}$. Meanwhile, the deflection angle at the n -th dark fringe is $\Delta \theta_n \cong 1.22 \frac{\lambda}{2R} + (n - 1) \frac{\lambda}{2R}$.

The deflection angle corresponding to the position of the n -th bright fringe is

$$\Delta \theta'_n \cong 1.22 \frac{\lambda}{2R} + (n - 1 + 0.5) \frac{\lambda}{2R} = (n + 0.72) \frac{\lambda}{2R}$$

The momentum variation experienced by photons at the n -th bright fringe is

$$\Delta p = \frac{h}{\lambda} * \Delta \theta'_n = \frac{h}{2R} * (n + 0.72)$$

Therefore, according to the equation governing the positions of bright fringes,

$$R \frac{2r_n}{(g_0 + R - r_n)^2} - 0.11 = \frac{n + 0.5}{2}$$

We obtain

$$r_n = \left[(g_0 + R) + \frac{2R}{n + 0.72} \right] \pm \sqrt{\left[\frac{2R}{n + 0.72} \right]^2 + 2(g_0 + R) * \frac{2R}{n + 0.72}}$$

And we use

$$(g_0 + R - r_n) = \mp \sqrt{\left[\frac{2R}{n + 0.72} \right]^2 + 2(g_0 + R) * \frac{2R}{n + 0.72} - \frac{2R}{n + 0.72}}$$

the value of the uncertainty relation reads

$$\begin{aligned} \Delta x \Delta p &= u \Delta t * \Delta p = u \frac{(\Delta p)^2}{F_{\perp u}} = u \frac{\left(\frac{h}{2R} * (n + 0.72) \right)^2}{\frac{hu}{(g_0 + R - r_n)^2}} = h \left(\frac{(n + 0.72)}{2R} * (g_0 + R - r_n) \right)^2 \\ &= h \left(\sqrt{1 + 2(g_0 + R) * \frac{(n + 0.72)}{2R}} - 1 \right)^2 \end{aligned}$$

Subject to the constraints $g_0 \leq 2R$ and $n \geq 1$, we set $n = 1$ and $\frac{2(g_0 + R)}{2R} \sim 1$. Thus, we obtain the minimum value $(\sqrt{2.72} - 1)^2 h = 0.4215h \geq \frac{h}{4\pi}$.

Therefore, the theory is not contradictory to quantum mechanics. On the contrary, without introducing any assumptions of wave superposition or interpretation of probability density, the present theory can still yield macroscopic diffraction results consistent with traditional theories. This fully demonstrates that this work reinterprets diffraction phenomena from a completely new mechanical perspective, providing a more self-consistent and intuitive physical picture for understanding the nature of quantum mechanics.

12. Outlook

The present work is not fully comprehensive, and multiple aspects remain to be further refined. Accordingly, we propose several highly challenging research topics for interested readers to extend and improve upon this study.

(1) The parameter $Q_1 = -0.11$ is intrinsically coupled to the geometric shape of circular apertures. If the fundamental modulation constant Q_1 can be derived purely from the intrinsic properties of the diffractive aperture without relying on calibration via measured Airy ring positions, this scheme would enable us to explore the essential nature of diffraction from a deeper microscopic perspective. Nevertheless, it constitutes a brand-new research project with heavy workload.

This task goes far beyond merely calculating the modulation constant for circular apertures; systematic verification for other diffractive geometries including single slits, square apertures and so on is also required. Sufficient cross validation across diverse aperture configurations is indispensable to guarantee adequate persuasiveness of the conclusions.

(2) This paper postulates that the velocity-perpendicular interaction force and electromagnetic force belong to two distinct physical dimensions and are mutually independent.

It remains an extremely challenging open problem whether a quantitative correspondence between this novel interaction and classical electromagnetic force can be established, and if so, how such a correspondence could be constructed.

(3) Now, the velocity-perpendicular interaction force proposed in this paper is only introduced as a theoretical hypothesis, which has not been rigorously derived from Maxwell's equations, quantum optics, quantum electrodynamics (QED) or standard effective Hamiltonians. Two core issues remain to be further explored: first, whether the proposed velocity-perpendicular interaction force can be derived based on classical quantum theory; second, whether this force model can be coupled with other mature theories, for instance, whether fundamental quantum equations such as the Schrödinger equation can be deduced from the proposed model.

13. Conclusions

In this study, we have proposed for the first time a novel interaction force that is inversely proportional to the square of the distance and directed perpendicular to the velocity direction. Based on the consideration of the interaction force between photons and the circular aperture, we have comprehensively interpreted the phenomenon of circular aperture diffraction from a mechanical perspective. The theoretical results obtained from our physically motivated heuristic model are in excellent agreement with calculations based on the conventional Huygens–Fresnel principle. Furthermore, this heuristic model can additionally account for the non-zero background intensity observed at dark fringe positions in experiments [27–31] and connect with current single-photon measurement experiments [21–26], phenomena that cannot be well explained by traditional theories. The theoretical framework established herein reveals that such interaction forces are modulated by the wave–particle duality of the research object, with the modulation quantity determined by the force itself, the net interaction time, and the characteristic scale of the system. All results demonstrate that, in addition to interpretations based on the wave theory of light, circular aperture diffraction can also be elaborated using the mechanical interpretation model proposed in this work. Notably, this work constitutes a distinct theoretical approach that entirely bypasses the Huygens–Fresnel principle, providing an alternative fundamental perspective for understanding light diffraction. The velocity-perpendicular interaction force elaborated in this paper is expected to lay a new theoretical foundation not only for the development of optics but also for advancements in quantum mechanics and related disciplines.

Interaction between substances is the most fundamental and core research object in the entire field of physical science. From Newtonian mechanics and electromagnetic theory to quantum mechanics, research on the interaction between micro-particles and macro-materials has continuously expanded the boundaries of human cognition. However, these breakthroughs have also been accompanied by deeper puzzles regarding the quantum nature and interdisciplinary theoretical bottlenecks. The velocity-perpendicular interaction force theory proposed in this work is anticipated to reshape people's understanding of the quantum nature.

Funding: Project supported by the National Natural Science Foundation of China (Grant Nos. 12375014 and 11875149), the Youth Jing-gang Scholars Program of Jiangxi Province, China and the Program of Qingjiang Excellent Young Talents, Jiangxi University of Science and Technology.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request. All data that support the findings of this study are included within the article.

Conflicts of Interest: The author declares no conflicts of interest.

References

- Born, M.; Wolf, E. *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, 7th ed.; Cambridge University Press: Cambridge, UK, 1999.
- Bethe, H.A. Theory of diffraction by small holes. *Phys. Rev.* **1944**, *66*, 163. [[CrossRef](#)]
- Bouwkamp, C.J. On Bethe's theory of diffraction by small holes. *Philips Res. Rep.* **1950**, *5*, 321.
- Bouwkamp, C.J. Diffraction theory. *Rep. Prog. Phys.* **1954**, *17*, 35. [[CrossRef](#)]
- Kottler, F. *Progress in Optics*; Wolf, E., Ed.; Elsevier: Amsterdam, The Netherlands, 1967; Volume 6, p. 331.
- Krupych, O.; Mys, O.; Dudok, T.; Say, A.; Vlokh, R. Effect of polarization ellipticity of the incident optical wave on acousto-optic diffraction efficiency and intensity modulation: Case of TeO₂ crystals. *Appl. Opt.* **2025**, *64*, 8308–8313. [[PubMed](#)]
- Gonçalves, M.R.; Rozenman, G.G.; Zimmermann, M.; Efremov, M.A.; Case, W.B.; Arie, A.; Shemer, L.; Schleich, W.P. Bright and dark diffractive focusing. *Appl. Phys. B* **2022**, *128*, 51. [[CrossRef](#)]
- Wang, Q.Z.; Xia, X.P. Abnormal distortion and control of a Gaussian beam in circular aperture diffraction. *Appl. Opt.* **2021**, *60*, 10035. [[CrossRef](#)] [[PubMed](#)]
- Tavassoly, M.T. Fresnel diffraction is a basic quantum mechanical effect. *J. Opt. Soc. Am. B* **2021**, *38*, 2043. [[CrossRef](#)]
- Ahmad, M.; Kabalan, N.; Omran, S. An analytical study of the diffraction of light by a circular aperture using spherical harmonics for $n \leq 1$. *Int. J. Opt.* **2020**, *2020*, 3057674. [[CrossRef](#)]
- Zhao, Z.G.; Duan, K.L.; Lü, B.D. Focusing and diffraction by an optical lens and a small circular aperture. *Optik* **2006**, *117*, 253. [[CrossRef](#)]
- Zhang, Y.J.; An, H.C.; Zhang, D.; Cui, G.H.; Ruan, X.K. Diffraction theory of high numerical aperture subwavelength circular binary phase Fresnel zone plate. *Opt. Express* **2014**, *22*, 27425. [[CrossRef](#)] [[PubMed](#)]
- Wang, Z.-L.; Zhou, M.; Gao, C.-Y.; Zhang, W. Near-field properties of diffraction through a circular subwavelength-size aperture. *Chin. Phys. B* **2012**, *21*, 064202.
- Koushki, E.; Alavi, S.A. Diffraction of a partial temporal coherent beam from a single-slit and a circular aperture. *Opt. Commun.* **2019**, *441*, 33. [[CrossRef](#)]
- Dupraz, K.; Martens, A.; Rax, J.M.; Zomer, F. Diffraction of Gaussian and Laguerre–Gauss beams from a circular aperture using the moment expansion method. *J. Opt. Soc. Am. A* **2022**, *40*, 27. [[CrossRef](#)]
- Popov, E.; Nevière, M.; Sentenac, A.; Bonod, N.; Fehrembach, A.L.; Wenger, J.; Lenne, P.F.; Rigneault, H. Single-scattering theory of light diffraction by a circular subwavelength aperture in a finitely conducting screen. *J. Opt. Soc. Am. A* **2007**, *24*, 339. [[CrossRef](#)]
- Gündüz, O.T.; Leitgeb, E.; Sabah, C. Sub-diffraction photon trapping: The possible optical energy eigenstates within a tiny circular aperture with a finite depth. *Electronics* **2023**, *12*, 4832. [[CrossRef](#)]
- Romero, J.A.; Hernández, L. Diffraction by a circular aperture: An application of the vectorial theory of Huygens's principle in the near field. *J. Opt. Soc. Am. A* **2008**, *25*, 2040.
- Qian, H.; Lin, W.; Qi, X. Numerical simulation of Fresnel and Fraunhofer diffractions of monochromatic and white light. *Opt. Eng.* **2016**, *55*, 084104. [[CrossRef](#)]
- Li, J.L.; Zhu, S.F.; Lu, B.D. The rigorous electromagnetic theory of the diffraction of vector beams by a circular aperture. *Opt. Commun.* **2009**, *282*, 4475. [[CrossRef](#)]
- Margalit, Y.; Zhou, Z.; Machluf, S.; Rohrlach, D.; Japha, Y.; Folman, R. A self-interfering clock as a 'which path'. *Science* **2015**, *349*, 1205. [[PubMed](#)]
- Bertet, P.; Osnaghi, S.; Rauschenbeutel, A.; Nogues, G.; Auffeves, A.; Brune, M.; Raimond, J.M.; Haroche, S. A complementarity experiment with an interferometer at the quantum–classical boundary. *Nature* **2001**, *411*, 166. [[CrossRef](#)] [[PubMed](#)]
- Dürr, S.; Nonn, T.; Rempe, G. Origin of quantum-mechanical complementarity probed by a 'which-way' experiment in an atom interferometer. *Nature* **1998**, *395*, 33.
- Eschner, J.; Raab, C.; Schmidt-Kaler, F.; Blatt, R. Light interference from single atoms and their mirror images. *Nature* **2001**, *413*, 495. [[CrossRef](#)] [[PubMed](#)]
- Schmidt, L.P.; Lower, J.; Jahnke, T.; Schöbner, S.; Schöffler, M.S.; Menssen, A.; Lévêque, C.; Sisourat, N.; Taïeb, R.; Schmidt-Böcking, H.; et al. Momentum transfer to a free floating double slit: Realization of a thought experiment from the Einstein-Bohr debates. *Phys. Rev. Lett.* **2013**, *111*, 103201. [[CrossRef](#)] [[PubMed](#)]
- Zhang, Y.-C.; Cheng, H.-W.; Zengxu, Z.-Q.; Wu, Z.; Lin, R.; Duan, Y.-C.; Rui, J.; Chen, M.-C.; Lu, C.-Y.; Pan, J.-W. Tunable Einstein-Bohr recoiling-slit gedankenexperiment at the quantum limit. *Phys. Rev. Lett.* **2025**, *135*, 230202. [[PubMed](#)]
- Jönsson, C. Elektroneninterferenzen an mehreren künstlich hergestellten Feinspalten. *Z. Phys.* **1961**, *161*, 454.
- Merli, P.G.; Missiroli, G.F.; Pozzi, G. On the statistical aspect of electron interference phenomena. *Am. J. Phys.* **1976**, *44*, 306. [[CrossRef](#)]
- Zeilinger, A.; Gähler, R.; Shull, C.G.; Treimer, W.; Mampe, W. Single and double-slit diffraction of neutrons. *Rev. Mod. Phys.* **1988**, *60*, 1067. [[CrossRef](#)]

30. Cronin, D.; Schmiedmayer, J.; Pritchard, D.E. Optics and interferometry with atoms and molecules. *Rev. Mod. Phys.* **2009**, *81*, 1051. [[CrossRef](#)]
31. Hornberger, K.; Gerlich, S.; Haslinger, P.; Nimmrichter, S.; Arndt, M. Colloquium: Quantum interference of clusters and molecules. *Rev. Mod. Phys.* **2012**, *84*, 157. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.