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Research Article

Keywords: hybrid-asymmetrical double-slit experiment, single-photon selfinterference, near-field Fresnel transition pre-Fraunhofer condition, wave-particle duality, complementarity principle

Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11267642/v1>

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Additional Declarations: No competing interests reported.

A Hybrid-Asymmetrical Double-Slit Interference Experiment in the Near-Field Transition Pre-Fraunhofer Condition

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02 October 2026

Abstract. The paper presents the results of a quantum interference study using an asymmetrical double-slit experiment with a low-intensity laser beam, conducted in the single-photon approximation and the Fresnel near-field transition pre-Fraunhofer condition. In addition to the temporal separation achieved by recording each particle individually, the hybrid-asymmetrical double-slit design (in both width and height) also allows spatial separation of the first satellite diffraction bands created by each slit, thereby minimising the mixing background effects from the opposite slit. Isolating the satellite bands of a diffraction pattern from one of the two slits enables which-way identification of the quantum particle, contributing maximally to the path-distinguishability parameter $D = 1$. Within these satellite bands, we observed interference fringes with reliability at their diffraction peaks for the wide slit and the narrow slit. After subtracting multiphoton-mixing interference noises $V(\text{mix})$, we obtain significant single-photon wave visibility values $\langle V1(sp) \rangle = 0.051 \pm 0.009(\text{stat.}+\text{sys.})$ and $\langle V2(sp) \rangle = 0.065 \pm 0.009(\text{stat.}+\text{sys.})$, respectively, at the wide-slit I_1 and narrow-slit I_2 diffraction bands. The results suggest the possibility of establishing an unusual

correlation, $D + V > 1$, in which a significant number of photons exhibit both wave and particle properties simultaneously within the same experimental spectrum. This differs from the Copenhagen interpretation and therefore requires further explanation.

Keywords. hybrid-asymmetrical double-slit experiment, single-photon self-interference, near-field Fresnel transition pre-Fraunhofer condition, wave-particle duality, complementarity principle

PACS numbers: 03.65.-w, 03.65.Ta, 42.50.Xa

1. Introduction

At the dawn of the new millennium, thanks to advanced technologies, the concept of the double-slit interference experiment using a single-particle beam, proposed by Feynman [1] to shed light on the deepest mysteries of quantum mechanics, was successfully realised. This fundamental physics problem originated from the Einstein-Bohr debate of 1927. Young's low-intensity beam double-slit experiments were initially conducted with photons [2] and later with electrons [3, 4]. Currently, the majority of the physics community accepts the Copenhagen interpretation, based on the wave-particle complementarity principle [5, 6]. It has been determined that probabilistic wave properties are inherent to the nature of each quantum entity, and not solely arise from large sets of particles [7, 8, 9, 10, 11, 12, 13]. However, the physical reality of an individual quantum entity remains a subject of debate, largely centred on philosophical interpretations, requiring further experimental verification. Numerous similar experiments involving photon beam splitting have also been performed using Mach-Zehnder interferometers (MZI), incorporating effects such as delay choice and quantum erasure [14, 15, 16, 17, 18], most of which align with the principle of wave-particle complementarity and support the Copenhagen interpretation (see the review in [18]). Note that there is another analysis [19] which suggests that both complementary attributes can coexist in a measurement setup, but only one of them is visible, while the other is obscured. Therefore, neither the delayed choice nor the quantum eraser can be used as proof of the disappearance of any wave or particle properties for verification of the complementarity principle. For instance, in a recent Young-Feynman experiment using a monochromatic electron beam and symmetrical double slits [20], blocking one slit, which causes the interference pattern to vanish, was the necessary trade-off for determining the particle's path. Conversely, an experiment using an asymmetrical double-slit system [21], through observation of the near-field (Fresnel) region and application of pre-Fraunhofer conditions, allows the electron beam to be separated into two distinct spectral components without physical intervention. Notably, experiment [21] simultaneously recorded interference fringes in the single-particle diffraction patterns but concluded that this phenomenon arose from the synchronisation of quantum wave branches from the two slits, thereby erasing information regarding the particle's path within the interference fringes [22]. Since 2021, we have conducted asymmetrical double-slit experiments in the Fraunhofer far-field condition using the single-photon approximation [23, 24]. We define the single-photon approximation as being achieved when the photon flux is low, for instance, with a laser power below 0.3 mW, corresponding to an intensity $I_L < 10^{15}$ photons. s^{-1} , such that, on average, no more than one photon is detected per laser wavelength. At even lower fluxes, a vast number of wavelengths must pass before a single quantum reaches the observation point, leaving virtually no chance for two synchronised photons within the same wavelength to interfere with each other. In reality, the situation is more complicated due to a limitation of digital cameras' temporal resolution (approximately 10-100 nanoseconds),

requiring us to reduce the beam intensity to 10^7 photons.s⁻¹ per camera pixel. In experiments [23, 24], we not only fabricated slits of unequal widths but also introduced asymmetry in the laser intensities passing through each slit. Measurements taken at the first main minima (coinciding with the position of a missing interference order) provided experimental evidence of the simultaneous observation of both wave-like and particle-like characteristics within the same interference spectrum [25]. This finding contradicts the complementarity principle, which governs the path distinguishability D , characterising particle-like behaviour and interference visibility V , characterising wave-like behaviour, within the correlation limit $D + V \leq 1$, as interpreted for asymmetrical double-slit interference [26]. Unable to find any other effective justification for the wave-particle complementarity observed in the experiment described in [24, 25], the analysis accepted an anomalous correlation between the two quantities representing wave-particle duality, specifically, a sum of $D + V > 1$, which contradicts the Copenhagen interpretation. Conversely, this result aligns with the non-local de Broglie-Bohm (dBB) double-solution interpretation [27, 28, 29]. To further investigate this anomaly, we recently improved the fabrication of the double-slit to achieve greater precision. We introduced asymmetry in both the width and height of the slits and employed a spectral isolation method under near-field conditions, similar to the electron experiment in [21], thereby enabling the observation of new spectral structures in greater detail and completeness than in previous asymmetrical double-slit interference experiments. This report presents the experimental method and results, which offer new evidence for testing the principle of wave-particle complementarity. The paper is organised as follows: Section 2 introduces the methodology; Section 3 presents the results of the spectral analysis; and Section 4 provides a discussion.

2. Method

In the Young-Feynman double-slit experiment, a necessary condition is the observation of interference phenomena involving individual quantum entities, whether electrons or photons. The minimal single-particle wave function for an electron or photon can be represented as a superposition of two amplitude branches with equal magnitude and intrinsic polarisation in the phase space, featuring a phase shift of $\delta = \pi/2$, specifically:

$$|\psi_i\rangle = \frac{1}{\sqrt{2}} \cdot (|\psi_V\rangle + i|\psi_H\rangle). \quad (1)$$

Here, the index V denotes vertical polarisation, and H denotes horizontal polarisation [25]. Consequently, the intrinsic curvatures of the geodesic equation can be described using a cylindrically twisted space-time model [30]; upon linearization, this transforms into a representation of propagating waves within a flat 4D Minkowski space-time (as proposed in [31]). Interference experiments utilising asymmetrical double slits [23, 24, 25] offer the opportunity to observe the structure of spectral components and reveal particle-like characteristics embedded within the wave spectrum, thereby allowing for the verification of the wave-particle complementarity principle. In this

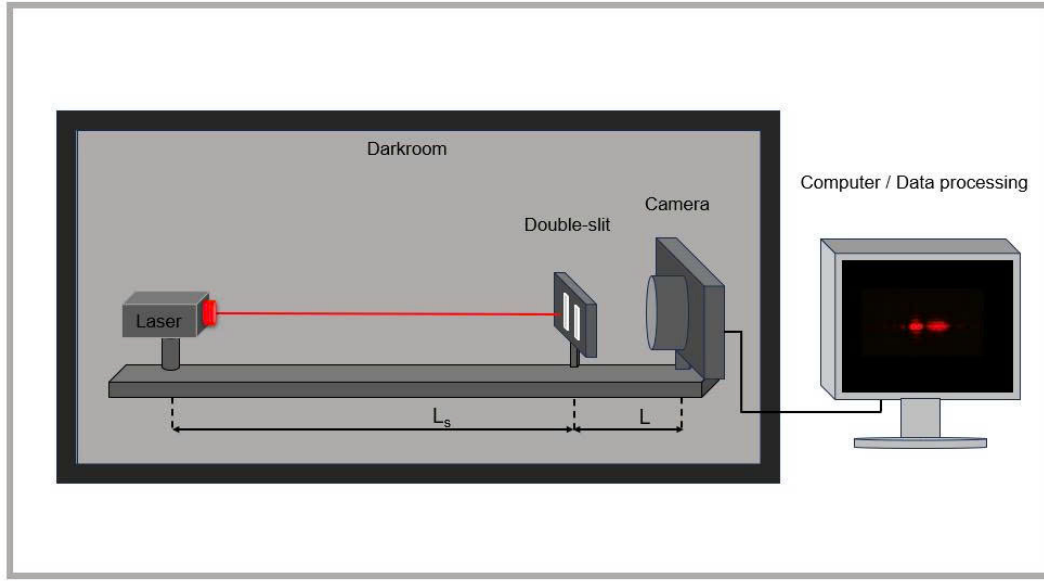


Figure 1. Scheme of the asymmetrical double-slit experiment

study, mirroring the electron beam experiment [21], we conducted observations in the pre-Fraunhofer condition (where the Fresnel number for the narrow and wide slits is $N_F = 0.12 < 0.34 < 1$.) at a distance $L \leq 100$ mm between the double-slit diaphragm and the camera screen, following the setup shown in Figure 1. At this distance, the distribution of each spectral component is approximately described by Fraunhofer diffraction, barring certain secondary deformations caused by near-field Fresnel diffraction contributions. We used a red laser source (wavelength $\lambda = 650 \pm 30$ nm, maximum power 4.5 mW) positioned at L_s from the double-slit diaphragm, far enough to reduce the photon flux passing through the slits effectively. The laser power was attenuated to a moderate level $W_1 = 0.6$ mW or a weak level $W_2 = 0.2$ mW, and the beam diameter expanded from $\Phi \leq 2$ mm to $\Phi \approx 20$ mm over the distance L_s ; this reduced the intensity of photons reaching the first-order diffraction pattern by 400 times, resulting in a flux of 1.7×10^{11} to 5×10^{12} photons. s^{-1} , thereby satisfying the condition for single-photon behaviour per laser wavelength, when incident on a satellite diffraction band. The imaging camera utilises a Sony IMX477R CMOS sensor with the following specifications: a resolution of 4056×3040 (12.3 MP), a sensor size of 1/2.3 inch (7.9 mm diagonal), and a pixel size of $1.55\mu\text{m} \times 1.55\mu\text{m}$. With an average signal accumulation time per pixel of approximately 7 nanoseconds (in practice extending to about 10 nanoseconds), the system still maintains the ability to distinguish between successive pulses, as long as the laser intensity incident on each pixel does not exceed 10^8 photons. s^{-1} . In the experiment, with the camera positioned at a distance of $L \approx 100$ mm from the slit, the photon beam passing through each slit diffracts onto a screen area spanning approximately 200 rows by 500 columns (10^5 pixels); this reduces the average intensity per pixel to 2×10^7 photons. s^{-1} , thereby allowing for the resolution limit of

Table 1. Characteristic dimensions of the double-slit experiment (μm)

Experimental set – up	Wide slit <i>Width</i> (b_1) <i>Height</i> (h_1)	Narrow slit <i>Width</i> (b_2) <i>Height</i> (h_2)
<i>Configuration A</i>	150. 300.	90. 450.
<i>Configuration B</i>	150. 450.	90. 300.
<i>Effective Slits Spacing, d</i>	910.	910.
<i>Laser – Slit Distance, L_S</i>	1250000.	1250000.
<i>Slits – Screen Distance, L</i>	91000.	91000.

individual photon-induced electronic pulses. However, the random temporal distribution of signal pulses leads to significant overlap between pulses arriving in close succession, particularly at the spectral peaks. Comparative analysis of spectra at varying laser intensities reveals this overlap effect, manifesting as a reduction in the observed pulse count relative to the true spectrum, which is most pronounced at the main central spectral peak at the moderate intensity level W_1 . For satellite spectral bands, the overlap phenomenon is largely negligible. Provided that overlap and saturation effects are not excessive, corrections can be applied using calculations analogous to those used for pixel dead time [24]. The distance L from the double slit to the camera surface is set so that the spectral components, I_1 and I_2 , are separated along the horizontal x-axis but remain nearly adjacent, with a distance of approximately one interference fringe. This arrangement allows full-detail observation of each spectral band without information loss from excessive overlap. The slit widths were fabricated similarly to the asymmetrical double-slit experiment [24], with the wide slit b_1 being approximately twice as wide as the narrow slit b_2 . However, unlike previous setups, we introduced asymmetry in the slit heights as well, $h_1 = 2/3.h_2$ in configuration A (referred to as slits A), or conversely, $h_1 = 3/2.h_2$ in configuration B (referred to as slits B). Specific dimensions, measured with less than 3% accuracy, are listed in Table 1.

For the transition region, the Fraunhofer approximation, as the simplest and most suitable model, needs to be adjusted when the two components of the diffraction spectrum, $I_1(x_1)$ and $I_2(x_2)$, are separated, which are calculated in the same way as in [24, 25]. If this theory works well enough, it will help extrapolate the true nature of overlapping spectral regions, especially in assessing multiphoton background mixing in single-photon diffraction and interference models. Isolating individual photon events in these two-component spectra, both in time and space, requires consideration of the potential for self-interference of each photon. The equation of the summation interference spectrum reads as follows:

$$I_S^{int}(x) = [I_B(x) - I_D^{sp}(x)] + I_V^{sp}(x) + I_V^{mix}(x); \quad (2)$$

with single-particle diffraction backgrounds (without multiphoton mixing):

$I_B(x) = |I_1(x) - I_2(x)|$; $I_D^{sp}(x) = \frac{1}{4} \cdot P \cdot (1 + f_1) \cdot (1 - R) \cdot [1 - f_2(x)] \cdot I_B(x)$;
and single-particle self-interference contributions:

$$I_V^{sp}(x) = I_D^{sp}(x) \cdot 2 \cdot \cos^2 \left(\frac{\pi \cdot d \cdot x}{L \cdot \lambda} \right); \quad (3)$$

while multiphoton mixing interference contributions read:

$$I_V^{mix}(x) = I_D^{mix}(x) \cdot [1 - f_2(x)] \cdot f_3 \cdot 2 \cdot \cos^2 \left(\frac{\pi \cdot d \cdot x}{L \cdot \lambda} \right); \quad (4)$$

with: $I_D^{mix}(x) = I_S(x) - I_B(x)$; and $I_S(x) = I_1(x) + I_2(x)$,
where R is the relatively greater intensity (in %) of either I_1 or I_2 ; f_1 is a parameter characterising the overlap, while $f_2(x)$ describes the phenomenon of increasing decoherence with distance from the optical center. The parameter $P = 0.5$ in the expression $I_D^{sp}(x)$ represents the maximum phase-matching capability due to the polarisation constraints of the individual particle waves (1), while the coefficient $1/4$ reflects the limitations on the solid angle distribution of the odd wave branches as they propagate from the corresponding secondary slit to the observation screen and synchronise with the individual particle waves (1) within an interference fringe, as proposed in our recent interpretation [30]. Those "near-field" factors are incorporated into the traditional Fraunhofer diffraction equation. The parameter f_3 is adjusted in the range $\{0 - 1\}$, where the multiphoton interference effect from the mixing band $I_D^{mix}(x)$ will be maximised (corresponding to the value $f_3 = 1$) to set the upper limit for the evaluation process. Under near-field Fresnel conditions bordering the Fraunhofer regime, photons from the main peak spill over into the sideband regions. We assess photon leakage through near-Fresnel diffraction spectra along the vertical axis, correcting for the parameter f_1 (varying in the range $\{0 - 1\}$) to increase the number of photons participating in the interference process. The satellite bands are isolated to evaluate wave-like behaviour (manifested by interference fringes) and particle-like behaviour (determined by tracing the path of a single photon). It should be noted that in traditional symmetrical double-slit interference experiments with identical slit heights ($h_1 = h_2$), spatial separation between the two component spectra is impossible.

3. Data processing and results

3.1. Isolated diffraction patterns through the narrow-slit: Configuration A

To process experimental data obtained from camera images, we used the Python programming language to digitise and read the light intensity values at each pixel. The background value was determined by calculating the arithmetic mean of the digitised intensities at the four corners of each image, where the signal light intensity is effectively zero. The experimental result represents the actual brightness value at each pixel, following background subtraction, within the 2D composite spectrum.

Presented below are the results obtained using Configuration A, which isolates the satellite bands of the I_2 component spectrum (produced by the narrow slit) against

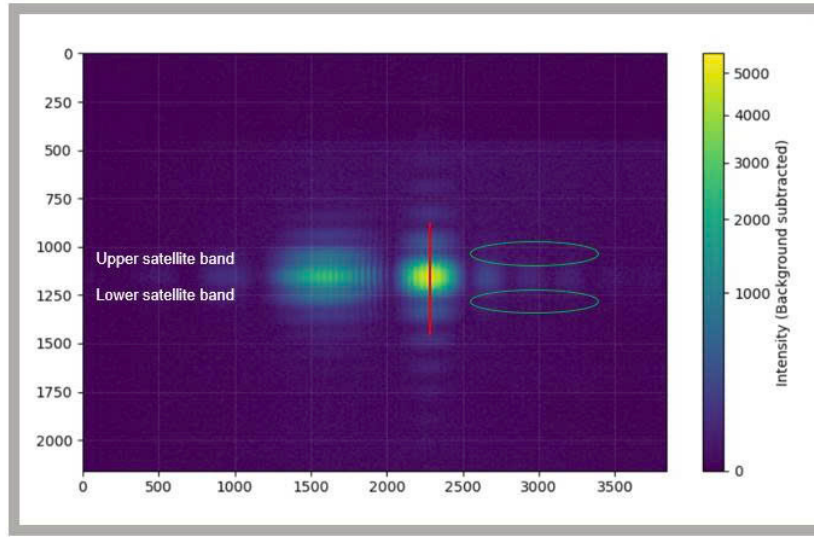


Figure 2. 2D spectrum for Configuration A, surveying the I_2 satellite bands

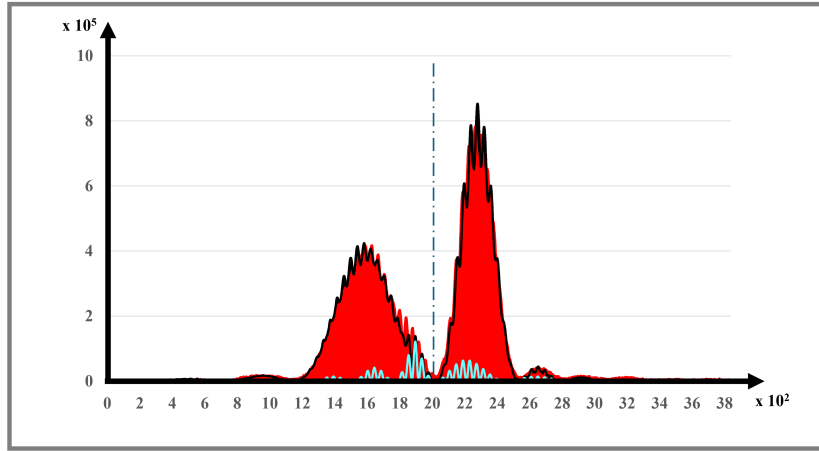


Figure 3. The central spectrum (red) in Configuration A compared with the Fraunhofer diffraction approximation (black) and the estimated multiphoton mixing (cyan). The vertical dashed-dotted line represents the central optical axis

a background relatively free of single-photon waves from the I_1 spectrum (produced by the wide slit). In the 2D composite spectrum shown in Figure 2, data for the I_2 -diffracted satellite bands (from the narrow slit) were extracted from the left; this involved summing 20 vertical channels at a vertical position (equivalent to the effective half-width of a single interference fringe) corresponding to the first main minimum of the I_1 -diffraction spectrum. The background in the horizontal channel range of 1200–2000 for the I_2 satellite bands is clearly defined, as it corresponds exactly to the data in the 2550–3450 channel range within the right-hand ovals, the regions symmetrical to the main I_1 spectrum (from the wide slit) across the vertical red axis. Although residual signal from the wide-slit I_1 spectrum spills into the main minimum region,

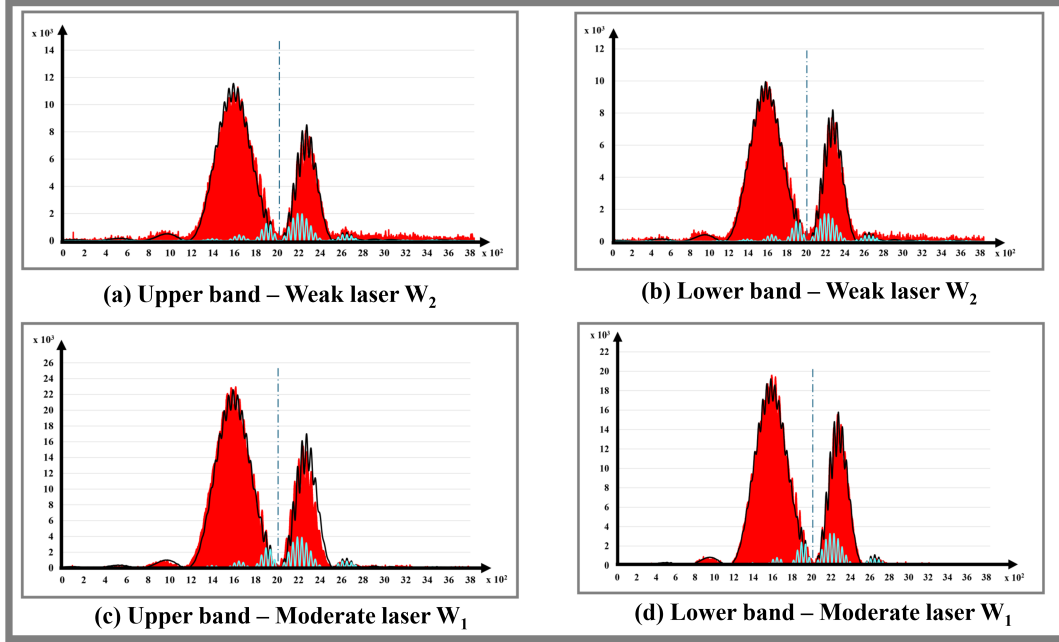


Figure 4. Satellite bands of I_2 in Configuration A: with weak laser (a,b) and moderate laser (c,d). The distribution curves show Experimental spectra (red) versus Theoretical Fraunhofer diffraction approximation (black) and estimated multiphoton mixing (cyan). The vertical dashed-dotted line represents the central optical axis

the resulting intensity ratio (R_{min} in %) at this vertical position is significantly lower than that of the main central spectrum. Furthermore, the area within the ovals, where the satellite bands of the I_1 residual signals would appear, is remarkably clean. From the 2D composite spectrum, we can extract data segments to construct 1D spectra along the horizontal (x-axis) channels corresponding to the central band and the two satellite bands located above and below it. We will experimentally analyse these 1D spectra and compare them with the Fraunhofer diffraction model. Figure 3 shows the original one-dimensional central spectrum of Configuration A, in a weak laser of W_2 power, in which the peaks from the wide-slit component (I_1) and the narrow-slit component (I_2) are distributed separately and adjacently along the horizontal axis with intensities $RI(A) = I_2 : I_1 = 47\% : 53\%$. The theoretical Fraunhofer diffraction approximation is applied here, following Equations (2)-(4). Configuration A satisfies the Fraunhofer approximation condition ($N_F = 0.12$) quite well, although small signs ($\leq 5\%$) of near-region Fresnel diffraction along the vertical axis still exist; this somewhat reduces the uniformity of the interference as it moves away from the central optical axis (vertical dashed-dotted line). The results of diffraction comparisons using the Chi-square test show that, except for some overlapping regions, the diffraction spectral peaks along the horizontal axis are described quite closely to theory, especially at the peaks of the satellite bands. As noted, due to Fresnel conditions affecting the vertical diffraction distribution, the first main minimum is not ideally "clean."

Table 2. Wave-visibility at the peaks of the spectral bands-Configuration A

Spectra	V4_{exp.} (Error)	V4_{theor.} (Deviation)%	V4(mix) (Error)	V4_{exp.}(sp) (±Error)	RI(A) I₂% : I₁%
(1)	(2)	(3)	(4)	(5)	(6)
Weak				(5) =	(2) – (4)
Laser W₂ :					
<i>Central</i>	0.096	0.095	0.042	0.054	47 : 53
<i>Spectrum</i>	(11)	(4.5 – 6.7)%	(9)	(±0.014)	
<i>Upper</i>	0.075	0.074	0.014	0.060	72 : 28
<i>Satellite</i>	(17)	(5.0 – 7.5)%	(6)	(±0.018)	
<i>Lower</i>	0.087	0.087	0.012	0.075	70 : 30
<i>Satellite</i>	(10)	(3.3 – 4.6)%	(4)	(±0.011)	
Moderate					
Laser W₁ :					
<i>Upper</i>	0.073	0.075	0.015	0.060	72 : 28
<i>Satellite</i>	(12)	(3.8 – 5.5)%	(5)	(±0.013)	
<i>Lower</i>	0.094	0.094	0.017	0.077	70 : 30
<i>Satellite</i>	(12)	(4.2 – 5.9)%	(6)	(±0.013)	
Single photon	Spectrum				
from Fig.8(a) :					
Summation	0.075	0.086	0.013	0.061	72 : 28
<i>of Satellites</i>	(7)	(3.4 – 4.8)%	(4)	(±0.008)	

Consequently, at the central axis of the upper and lower satellite bands, and for both moderate (W_1) and weak (W_2) laser power intensities shown in Figure 4(a–d), a residual photon peak from the I_1 spectrum still intrudes into the minimum. This residual intensity from I_1 is approximately $I_1 \approx 30\%$, small relative to the I_2 satellite-band's intensity, and is effectively isolated from the satellite band of the I_2 spectrum. Only a small portion of the corresponding I_1 sidebands on the left might blend with the I_2 satellite band, primarily between channels 1200 and 2000, which can contribute to multiphoton interference. In the peak region of the I_2 satellite bands, photon contamination from I_1 is minimised and can be theoretically accounted for by Equation (4) and subtracted. Table 2 presents the main results. To ensure the wave-nature assessment, we do not use the interference fringes on the left or right flanks of each component; instead, we average the four interference fringes in the value V4 of the wave visibility at the peak region, which offers the highest statistical accumulation and the relatively low residual background interference from the I_1 spectrum. Thus, Column (2) contains the experimental interference contributions at the peak regions of

all diffraction bands. Compared with the theoretical diffraction distribution, using the Fraunhofer approximation and the Chi-square test, presented in Column (3) reports the upper deviation between theoretical and experimental data in the half-width region of the spectral peaks, where the maximum relative deviation at the diffraction peak is favorable, in $\Delta\% < (3\% - 5\%)$. Therefore, even under pre-Fraunhofer conditions, this theory still provides a satisfactory approximation, allowing identification of the diffraction components that contribute to the overall interference spectrum. In the central band in Figure 3, the components also show interference fringes with a structure and distribution very similar to those in the two satellite bands shown in Figure 4. One difference is that in Figure 3, photons from the subbands of I_1 along the x-axis overlap significantly with the main spectrum of I_2 (and vice versa), making central spectrum analysis more complicated (see the multiphoton-mixing contributions in Column (4), Table 2). The reliability of the multiphoton contamination assessment matches the theoretical diffraction calculations in Column (3), ensuring the final result's accuracy is not affected by the contamination subtraction process. Since the main spectrum accounts for approximately 95% of the intensity of each diffraction branch, the spatial overlap of photons from the two slits remains at 5% or less. Low statistics in the region further from the peak I_1 lead to relatively large errors when evaluating multiphoton mixing using diffraction theory. However, the absolute values of these uncertainties are still small enough not to obscure the physical signals, as can be seen in Column (4). It is noteworthy that for a W_2 -power weak laser, the photon flux through the double slit in the central spectrum in this experiment is $\leq 10^{12}$ photons. s^{-1} , which just meets the single-particle approximation. Consequently, this allows us to present data on the central spectrum to examine the nature of the interference fringes located there. In the experimental setup, various sources of systematic error must be taken into account, such as incomplete interference fringe resolution, geometric deviations of the optical axis, uneven selection of upper and lower satellite bands, etc. This problem has been effectively solved by the averaging method, combined with rich statistical data. As a result, the majority of the recorded interference value V_4 , averaged over Column (2) of Table 2, $\langle V_4 \rangle = 0.085 \pm 0.009$ (including systematic errors), is attributed to the central band and its satellite bands of the I_2 diffraction patterns of the narrow slit. However, the $V_4(\text{mix})$ multiphoton mixing of the central band is significantly greater than that of its satellite bands. If we apply a refined subtraction, as calculated in Equation (4), we can eliminate some of the contributions of the mixed noise $V_4(\text{mix})$ from the different single-photon waves passing through both slits. Then, the purely single-photon $V_4(\text{sp})$ self-interference components of I_2 become independent of the photons of the I_1 spectrum; these components can be considered identical across all spectral bands, including the central band and satellite bands. Table 2 lists the calculated wave-visibility V -values obtained from all spectral bands, corresponding to laser power levels W_1 and W_2 , except for the central spectral peak, which were calculated using only low laser intensities (W_2) because the higher-intensity powers (W_1) could cause saturation.

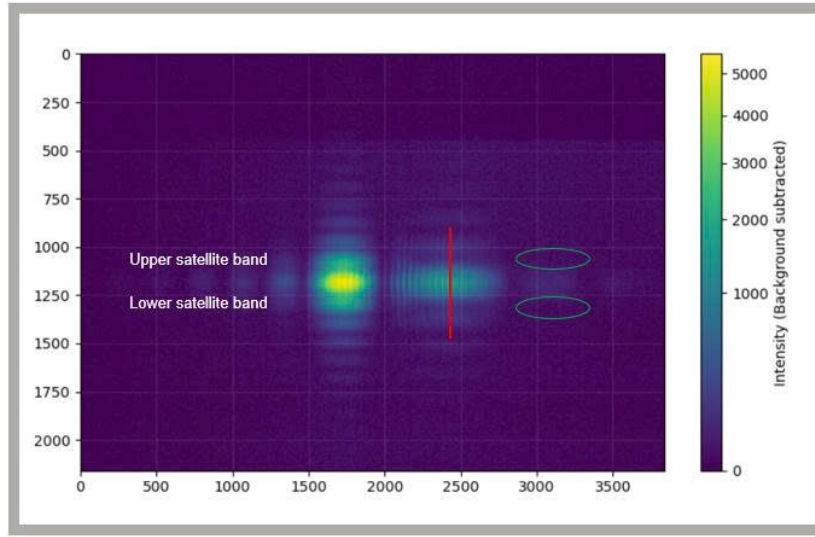


Figure 5. 2D spectrum for Configuration B surveying the I_1 satellite bands

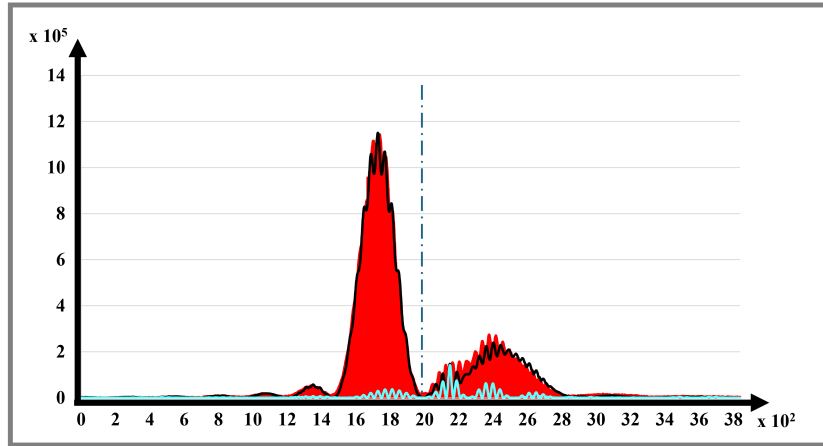


Figure 6. The central spectrum (red) in Configuration B compared with the Fraunhofer diffraction approximation (black) and the estimated multiphoton mixing (cyan). The vertical dashed-dotted line represents the central optical axis

3.2. Isolated diffraction patterns through the wide-slit: Configuration B

Similarly, in Figure 5 of the 2D composite spectrum for the slit configuration B, the diffracted satellite bands of spectrum I_1 (from the wide slit) are located on the left side. The symmetrically background to the right, enclosed by the oval, is remarkably free of interference from single-photon waves originating from the narrow slit of spectrum I_2 ; its magnitude is less than one-thousandth of the total satellite-band intensity of spectrum I_1 . In Figure 6, the photon intensity of the one-dimensional central spectrum passing through the narrow slit is lower, with the intensity ratio $I_2 : I_1 \equiv RI(B) \approx 77\% : 23\%$, which further highlights the difference in R_{min} values compared to Case A. The spectral patterns of this configuration are in satisfactory agreement with the Fraunhofer

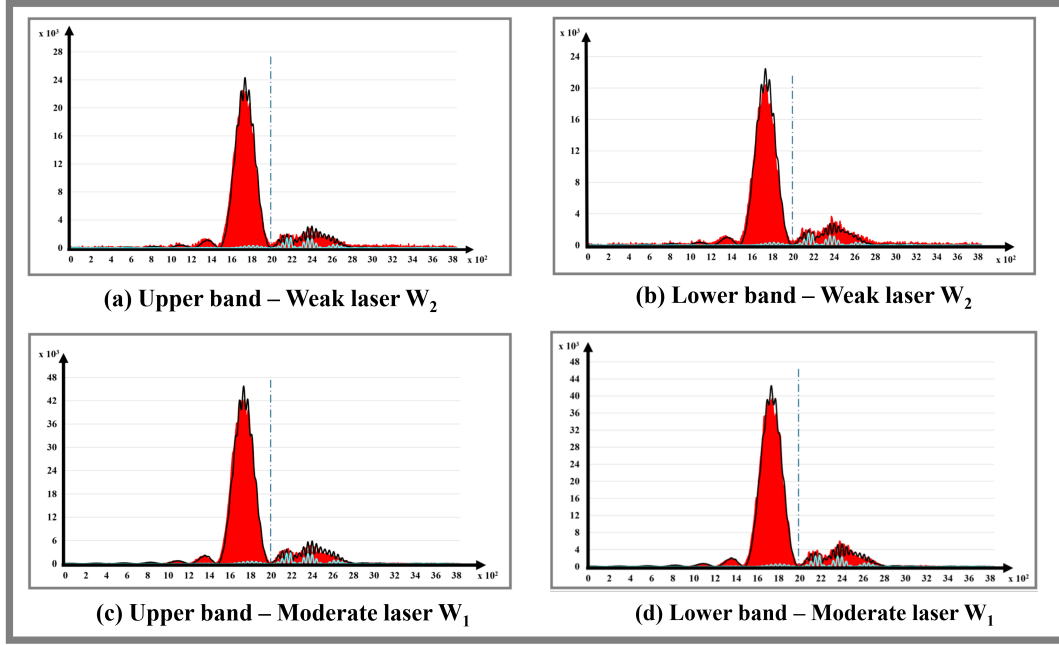


Figure 7. Satellite bands of I_1 in Configuration B: with weak laser (a,b) and moderate laser (c,d). The distribution curves show Experimental spectra (red) versus Theoretical Fraunhofer diffraction approximation (black) and estimated multiphoton mixing (cyan). The vertical dashed-dotted line represents the central optical axis

approximation, considering the corresponding Fresnel number $N_F(B) = 0.34$. We can also observe some side effects, such as a phase variation across the camera plane in Fresnel near-field diffraction (along the vertical axis), which causes a reduction in interference visibility, measured from the optical axis (vertical dashed-dotted line near channel 2000) outwards to the left or right, at the spectral peak. We made a minor correction to the peak intensity of the I_1 -spectral component of the central spectrum, potentially exceeding 10^{11} photons. s^{-1} , which could induce a degree of photon pulse pile-up, even when using the W_2 lowest-intensity weak laser setting, which increases the V3-value roughly by an adjustment less than 5%. Figure 7 shows that the number of scattered photons from the narrow slit entering the first main minimum of the vertical diffraction spectrum I_2 is also lower, with $I_2 : I_1 \equiv RI(B)_{min} = 13\% : 87\%$, which minimises the contribution of multiphoton signal mixing to the I_1 spectrum being investigated in Configuration B. It is clear that all observed satellite band peaks in Figure 7 are slightly lower than the true values of the original satellite spectra, but their distortion levels are lower than the central spectral peak in Figure 6. Therefore, we retained the original data without making any corrections, in order to demonstrate that this might only cause secondary bias in the interference fringes (i.e., within the experimental error range). Using the same analytical method for the central spectrum in Figure 6 and the satellite-band spectra (a–d) in Figure 7, we observed a wave-nature visibility $V > 0$. High statistical accumulation ensured a reliable estimate of

Table 3. Wave-visibility at the peaks of the spectral bands-Configuration B

Spectra	V3_{exp.} (Error)	V3_{theor.} (Deviation)%	V3(mix) (Error)	V3_{exp.}(sp) (±Error)	RI(B) I₁% : I₂%
(1)	(2)	(3)	(4)	(5)	(6)
Weak				(5)	=
Laser W₂ :					(2) – (4)
<i>Central</i>	0.066	0.066	0.011	0.055	77 : 23
<i>Spectrum</i>	(6)	(4.3 – 6.0)%	(5)	(±0.008)	
<i>Upper</i>	0.061	0.060	0.007	0.054	87 : 13
<i>Satellite</i>	(7)	(4.5 – 6.4)%	(4)	(±0.008)	
<i>Lower</i>	0.066	0.061	0.006	0.060	87 : 13
<i>Satellite</i>	(9)	(6.3 – 8.9)%	(5)	(±0.010)	
Moderate					
Laser W₁ :					
<i>Upper</i>	0.056	0.057	0.006	0.050	87 : 13
<i>Satellite</i>	(6)	(5.0 – 7.1)%	(4)	(±0.007)	
<i>Lower</i>	0.040	0.041	0.006	0.034	87 : 13
<i>Satellite</i>	(4)	(4.5 – 6.3)%	(4)	(±0.005)	
Single photon	Spectrum				
from Fig.8(b) :					
Summation	0.049	0.039	0.007	0.042	87 : 13
<i>of Satellites</i>	(7)	(2.1 – 2.9)%	(2)	(±0.007)	

the interference contribution to the measured V3 visibility by averaging the three most clearly resolved fringes at the peak. Table 3 lists the calculated wave-visibility V3-values obtained from all spectral bands, corresponding to laser power levels W_1 and W_2 for Configuration B. Averaging over all values in Column (2), the uncorrected wave visibility for the three interference fringes, V3, was obtained as $\langle V3 \rangle = 0.058 \pm 0.005$ (including systematic errors) in peak regions of the satellite bands added by one of the central spectrum I_1 . The values at the central spectral peaks were calculated using only the lower laser intensity (W_2) to avoid a significant saturation at the spectral peak.

3.3. Background vs. Effect studies

We also conducted additional experiments to determine how the interference phenomenon was affected by the unstructured background, noise unrelated to the two diffraction patterns I_1 and I_2 . More than 80% of this originates from noise in the camera system's electronics, while less than 20% consists of genuine, relatively stable background photons. When adjusting this background level relative to physical effects,

by varying the laser intensity or adjusting the scattering of ambient light entering the dark chamber, we found no impact on the interference ratios relative to the overall lateral spectral bands. In other words, the wave visibility values $V > 0$ remain strongly preserved. However, in weak signal regions, such as the 2850-3450 channel range, when using low-intensity laser beams, background noise is large enough to make it difficult to assess the multiphoton noise $V(\text{mix})$. We found that in satellite spectral bands with sufficiently high statistics and minimal multiphoton-mixing interference from the opposite slit, interference patterns recorded at spectral peaks exhibited high reliability. The probability of interference occurring between two individual optical wave branches passing through the two slits, coincident and synchronised purely by chance, is extremely low, as such events would not be confined within the diffraction envelope. Recall that similar random interference that carries no path-identifying information would nullify the path-distinguishability parameter D , thereby preserving the wave-particle complementarity principle, consistent with the conclusions drawn in [22] regarding the electron experiment [21]. In the present experiment, we did not observe such random, uncorrelated interference fringes; if they do exist, they are weaker than statistical fluctuations and can be considered negligible. Consider slits B, for example: the intensity of the observed interference fringes contributing to the total photon count in sub-branches of I_1 aligns with classical wave-optics predictions; they do not scatter randomly outside the diffraction envelope. Random wave components are not constrained by the diffraction envelope of the narrow slit; instead, they disperse isotropically according to the Huygens-Fresnel principle. Primarily, these consist of background photons that share no common origin with the single-photon wave (1) from the wide slit. Since the assessments from the aforementioned supplementary experiments indicate that the contribution of background photons (δB) to the interference effect does not exceed 0.5% of the peak intensity, consequently, the probability of a background photon synchronising with the single-photon wave (1) is similarly reduced, scaling with $\delta B < 10^{-2}$. Thus, random interference from background photons is negligible compared to statistical fluctuations. Another potential source is a non-random odd-wave branch that splits off from the single-photon wave (1) before passing through the secondary narrow slit, thereby bypassing diffraction at the slit edge. However, as it passes through a slit, free isotropic scattering further reduces the intensity of these odd-wave branches by a factor of 10^8 over a distance $L \approx 100$ mm to the camera surface, specifically at the cross-section of each interference maximum (covering approximately 20×20 pixels). This reduces the intensity to less than 10^4 photons. s^{-1} , eliminating the possibility of coincidence with the single-photon wave (1) from the wide slit. Thus, spherically symmetrical wave sources passing through the narrow slit do not randomly traverse it, nor can they contribute to interference within the diffraction pattern, contrary to the counter-arguments raised regarding electron interference experiments [21, 22]. In the present study, the observed interference effects, $V1 \equiv < V3 >$ (Configuration B) and $V2 \equiv < V4 >$ (Configuration A), significantly exceed statistical fluctuations at the diffraction peaks, given that the overall statistical error remains below 0.5%. Having

eliminated the aforementioned "random" and "non-random" extraneous wave sources, we now need to identify another type of extraneous wave originating from the secondary slit but intrinsically related to the single-photon wave (1) through the main slit of the satellite diffraction bands. This determination aims to understand the nature of the interference effect observed when $V > 0$, the state in which path information is preserved (i.e., $D = 1$).

4. Discussion

It should be noted that the near-Fraunhofer condition, where diffraction intensity (2) closely matches the far-field Fraunhofer distribution, serves as an acceptable approximation in this experiment. Except for some minor multiphoton mixing effects, the observed more significant wave visibility values would be attributed to the contribution of individual photons. For isolated photon events in time and space, the phenomenon of self-interference for individual photon raises a profound mystery: when undergoing interference, does the photon retain its particle-like nature? If it remains a particle that can only pass through one slit, how can it interfere with itself? Based on insights from interpreting previous experiments [25], we hypothesise the existence of extraneous, "odd" wave branches, generated by the individual photon wave (1) itself, passing through the secondary slit and then synchronising with the "mother" wave passing through the main slit to create self-interference. This concept closely reflects the "pilot wave" philosophy associated with de Broglie's matter waves in the de Broglie-Bohm double-solution theory [27, 28, 29]. Accordingly, upon exiting the corresponding slit, these odd-wave branches would exhibit a relatively free distribution, such as an isotropic spread governed by the Huygens-Fresnel principle. Consequently, if the point-particle events within the observed interference fringes can be attributed to the accumulated set of single-photon waves passing through, for example, the wide slit within the I_1 sub-spectrum, this implies that they simultaneously generate the wave-visibility value $V > 0$ and contribute to the path-distinguishability parameter D . We need to consider another possibility: is there any contribution, and if so, what is it, when a single-photon branch randomly appears to pass through the other (narrow) slit and accidentally coincides with a single-photon wave (1) within the I_1 diffraction spectrum? Due to the constraints of the Fraunhofer diffraction law, only wave-like photon sources, specifically those with individual wave components passing simultaneously through the opposing narrow slit, can reach positions within the diffraction pattern I_1 to interfere with one of the single-photon wave branches in Equation (1) originating from the wide slit. This is a phenomenon called multiphoton interference. Based on the Chi-square tests in Column (3), Table 2 or Table 3, the theoretical diffraction curves can fit experimental data within a margin of error of less than 5%, and the theoretical estimates resulting in the maximum multiphoton contribution vary within the accuracy range as shown in Column (4). Accordingly, in Equation (4) we take $f_3 = 1$ to reach an upper limit estimation. By subtracting the multi-photon mixing contribution $V(\text{mix})$,

we obtain the single-photon wave visibility $V(sp)$ listed in Column (5). Subsequently, by averaging the values across the spectral bands, we derive the significant empirical single-photon wave visibility values: $\langle V1(sp) \rangle = 0.051 \pm 0.009$ for Configuration B and $\langle V2(sp) \rangle = 0.065 \pm 0.009$ for Configuration A. Consider Case B for illustration again: assume that before the particle passes through the wide slit, an odd-wave branch emitted from the single-photon wave (1) scatters toward the opposite (secondary) narrow slit and subsequently acts as an interference agent with the mother wave (1) at the main wide slit. As an independent wave branch, it can propagate isotropically and re-enter the region of the diffraction band I_1 . Unlike the previously dismissed "randomly synchronised" free wave sources, these odd-wave branches at the secondary (narrow) slit are capable of optimal entanglement synchronisation with the mother single-photon wave (1) at the main slit, sharing the same wavelength for the self-interference. However, because this is a quantum probability wave and not an existing physical optical wave, it carries neither energy nor momentum. Nevertheless, quantum optics has demonstrated that probability waves obey the same laws of wave optics, including the principles of interference and diffraction. In the context of de Broglie-Bohm theory, this free (but non-random) wave branch can be considered a "guide wave" responsible for guiding the single-photon wave (1). If this is the only explanation, and there are no other plausible alternatives, then the observed interference fringes are confirmed to belong to the separate satellite subbands of I_1 of the diffraction spectrum. When this free-propagating odd-wave branch successfully synchronises with one of the two branches of the single-particle wave (1) within a diffraction-band spectrum, it guides the single-particle wave (1) toward the interference fringe formation site and contributes to a wave visibility value of $V > 0$, namely the single-particle wave visibility $V(sp)$. This phenomenon, where quantum wave components originating from a single-photon source (1) maintain synchronous coherence, can be termed the "self-interference" effect. Unlike interference caused by randomly synchronised sources, this self-interference effect allows the two branches of the single-particle wave (1) to be superposed after diffraction through the narrow slit to maintain coherence. This preserves the existence of quantum photons and maintains the maximum value of the path distinguishability $D = 1$. The degree of interference synchronisation depends on the ratio of the relative intensities of the photons passing through the two slits, as has been evaluated in recent studies [25, 31]. Accordingly, experimental data show that in the favourable case where the two component branches are balanced in intensity (i.e., $I_1 = I_2$), the maximum value of V-wave visibility is limited to $V < 0.5$. This is because, in the superposed wave arms of single photons (1) passing through the wide slit, only one arm possesses the intrinsic polarisation suitable for enhanced interference and amplitude amplification, at the time of synchronisation with the guiding wave arm coming from the narrow slit. All explanations for the Configuration B example above also apply to Configuration A. In the present experiment, after removing a small amount of multiphoton mixture, we successfully separated the single-particle interference spectrum, characterised by $V(sp) > 0$, from the satellite bands. Figure 8 illustrates the summation empirical

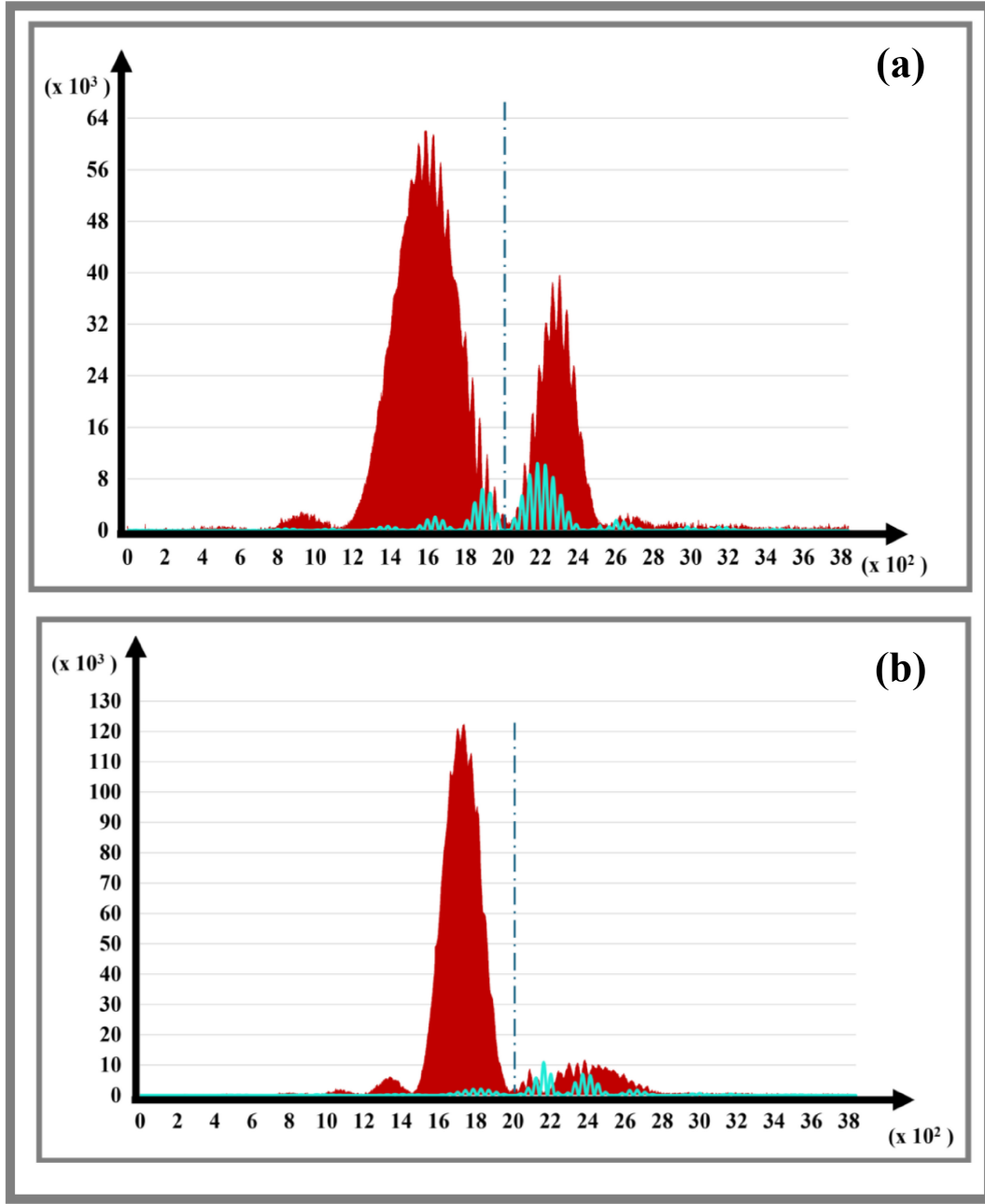


Figure 8. Single-photon summation empirical spectrum (red) of the satellite bands (after subtraction of multiphoton mixing) of the I_2 in Configuration A, Case (a), and that of I_1 in Configuration B, Case (b), vice-versa Multiphoton mixing (cyan)

spectra of the satellite bands derived from Figure 4 of the spectrum I_2 , Case (a) and from Figure 7 of the spectrum I_1 , Case (b). Note that, because the summation of the four satellite bands may reduce the resolution of the interference fringes, the V-values of the wave visibility of the two combined satellite spectra (as listed at the ends of Table 2 and Table 3) are lower than the previously recorded average values $\langle V1(sp) \rangle$ and $\langle V2(sp) \rangle$. However, the reliability of the experiment remains assumed. We

seem to be facing a scenario where the photon wave (1) simultaneously determines its path (identifies the slit it passes through, $D=1$) and creates interference fringes ($V > 0$). Therefore, the wave-particle duality correlation reaches an anomalous level when $D+V > 1$. This experimental evidence contradicts the Copenhagen interpretation, which posits that before passing through the double slit, one cannot distinguish between particle and wave, or even denies the particle's independent existence, regarding it merely as a potentiality. From that perspective, the particle only becomes observable after passing through a double slit, specifically, when the probability wave interacts with the measuring device, causing the quantum superposition wave function to collapse into a definite eigenstate, thereby transforming reality into something subjective and dependent on the act of observation. To date, the Copenhagen view remains widely accepted because no contradictions with empirical reality seem to have been found, except for the results recorded from the asymmetrical double-slit experiments. However, if experiments involving asymmetrical double-slit interference prove otherwise, then new research beyond long-existing explanations will be needed. But it is by no means an easy task. The reason is that objective physical reality in the microscopic world contains a series of contradictions that are difficult to resolve simply. Faced with that situation, we propose an approach, such as developing new explanations along the lines suggested in [31], whereby objective quantum reality encompasses both an "explicit" reality, manifesting as discrete point-like particles in ordinary 3D space and a "hidden" reality in the form of probability waves propagating continuously within an extended 3D time-like phase continuum. The hidden reality possesses neither energy nor observability, yet it carries information and is described by logical, mathematical, and physical laws. Essentially, these are two organic aspects of the same objective entity, viewed from different frames of reference and governed by a dual system comprising classical mechanical equations and quantum mechanical equations. This model is analogous to the de Broglie-Bohm dual-solution theory framework, although the system of equations established in [30] has been extended and closely linked according to the general principle of relativity.

5. Conclusions

In double-slit interference experiments with individual photons, we successfully separated the two diffraction components of each interference spectrum in the Fresnel transition pre-Fraunhofer condition. This result was achieved thanks to the asymmetrical double-slit design, which differs in both width and height. The separate spectral bands allow for the differentiation of the path with a maximal distinguishability D -factor of 1, similar to the single-slit diffraction experiment. Furthermore, we obtain the single-photon wave visibility $V(sp)$; and by averaging across all spectral bands, we derive the significant empirical single-photon wave visibility values: $\langle V1(sp) \rangle = 0.051 \pm 0.009$ (stat.+sys.) for diffraction pattern through the wide slit and $\langle V2(sp) \rangle = 0.065 \pm 0.009$ (stat.+sys.) for diffraction through the narrow slit. These new results

reaffirm the anomalous correlation $D + V > 1$ previously observed in Fraunhofer far-field experiments, a finding that challenges the expectations of the wave-particle complementarity principle. Nevertheless, further independent verification steps using single-particle beams of both photons and electrons are needed to investigate potential interference contributions from other sources and to rigorously assess the validity of the complementarity principle. Conversely, if the results of this experiment are not refuted, they would provide evidence consistent with the view of objective microphysical realism. This could contribute to solving fundamental problems in quantum mechanics that have persisted since the famous debate between Einstein and Bohr at the 5th Solvay Conference in late 1927.

Acknowledgement

We express our deepest gratitude to the Vietnam Atomic Energy Institute (VinAtom) for its dedicated support throughout this five-year experimental research project.

Author contributions

Th.V.V. proposed the idea of the experiment, directed the research, was involved in performing the measurements, data processing and analysis, and drafted the manuscript as the corresponding author. Th.N.T. and H.H.Ch. were responsible for the design and manufacture of double slits, while Dz.N.M. and H.N.Q. participated in performing the slit production; they all participated in running measurements. At the same time, H.N.Q. was responsible for data processing and analysis. Th.D.Q. and H.N.Th. were responsible for the electronic hardware design, setup of the experimental system, and running the measurements, contributing to data processing, including the Chi-square test. V.V.D. participated in measurements and in data processing. H.P.Th. developed software for supporting multi-processing of spectra, jointly performing data processing and analysis. V.V.D., H.P.Th. and Dz.N.M. were responsible for the design of graphics and figures. All co-authors participated in the group discussion and approved the final draft.

Data availability

The authors declare that the data sets generated during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests.

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