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Introducing wave-particle duality with low-cost quantitative experiments on light diffraction

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Abstract

We present a quantitative optical low-cost experiment aimed at introducing students to wave-particle duality from a phenomenological point of view. The experiment, focused on light diffraction, clearly shows the intermediate crossover regime which characterize the transition from geometric optics (in which light behaves like a stream of particles) to the Fraunhofer diffraction regime (where the wave aspects are most evident). It can also be considered for introducing students to the uncertainty relations through diffraction of light waves. The experiments do not require expensive materials or specific laboratory instruments and employ the sensors and camera of common mobile devices. The experiments were tested with master students in mathematics and physics, who aim at becoming high school teachers.

Keywords: wave-particle duality, physical optics, low-cost experiments

1. Introduction

The present paper aims at making students develop an intuitive grasp, mainly based on the formal analogy between quantum mechanics and classical optics, of two related quantum-mechanical phenomena, namely the Heisenberg uncertainty principle and the crossover between quantum and classical behaviour. In particular, we propose and exhibit an experimental activity based on physical optics, that can be presented to students in the classroom or even performed at home. It is based on the use of smartphone cameras as measuring instruments and consists of quantitative experiments, which can in addition help students achieve the typical learning goals of a laboratory course. The results of the experiment

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can in any case be interpreted on the grounds of usual wave optics, in particular Fraunhofer and Fresnel diffraction by a single slit.

On the other hand, in recent years, starting from the mentioned formal analogy and from other arguments (cf the introduction of [1]), the idea of using single-slit diffraction to introduce the uncertainty principle in a way suitable for an undergraduate or high school course [2] and has been used by many authors [3–5]. Some papers present in the literature provide both a theoretical analysis of single-slit diffraction and a lecture demonstration of the phenomenon using readily available equipment.

In the present paper, the analogy is extended to the transition from the geometric optics approximation to the Fraunhofer diffraction approximation, which are limiting cases of the more general Fresnel theory of diffraction. Indeed, the crossover between quantum and classical behaviour is analogous to the one between physical (wave) and geometric (ray) optics. As such, there is a strong connection to the idea of wave-particle duality, about which much research was conducted to explore the wave behaviour of matter. More than 20 years ago, Nairz *et al* [6] investigated wave-particle duality and the uncertainty principle for material objects. In their experiments, the authors clearly visualized the wave nature of matter and reported a demonstration of the uncertainty principle for such massive, complex objects as fullerenes. From the whole series of experiments, which were performed using slits of varying widths, the authors extracted the width values from the experiment and compared them with a quantum wave model. An excellent agreement between expectation and experiment was found throughout the whole range of values. They could distinguish essentially two different regimes corresponding to a pure quantum (wave) regime and a range which can be very well described using a classical corpuscular (ray) model (as we schematically show in figure 1).

In a didactic laboratory, such a crossover can be visualized, by exploiting the analogy, by optical diffraction experiments. Typically, however, this is achieved by using expensive variable-width slits [7]. In this paper, instead, we experimentally explore such crossover with much lower

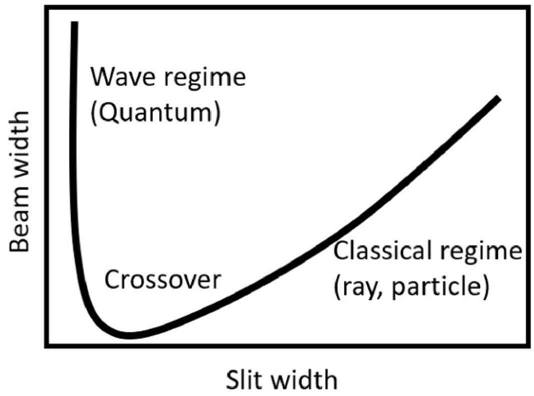


Figure 1. Qualitative behaviour of the width of the beam as a function of the width of the slit (adapted from [2]). Labels stress the analogy between the quantum results of [6] and wave optics.

cost materials. The experiment amounts indeed to the investigation of the light pattern produced on a screen by light rays going through a slit which has the shape of a V, i.e. has a width whose value varies as we move along the axis of the slit itself. Such a slit can easily be manufactured using very cheap cutter or razor blades. Our main experimental finding is that, if one restricts attention to analysing the width of the central maximum of the pattern, both regimes are simultaneously visible for the narrow and wide parts of the slit respectively and in addition, for intermediate widths, the crossover regime can be analysed. This intermediate regime corresponds in fact to Fresnel diffraction [8], since as the slit widens the conditions for Fraunhofer diffraction cease to hold. This clearly shows that there is no discontinuous jump from macroscopic geometric optics (ray or particle model) to microscopic wave optics (quantum model). On the contrary, students are shown a smooth transition from one regime to the other, with no cognitive disconnect between them. They see all the phases of the transition at once on the screen. The fact that in the low width region, where the wavelike nature dominates, the maximum becomes smaller as the width widens, when transposed to a quantum picture, where the beam is made of several quanta (typically, but not necessarily, photons), can be regarded as a consequence of the uncertainty principle (see [3–5] for details). In a quantum single-slit experiment, indeed, the width of the slit determines the accuracy with which the position of the quantum as it goes through the slit is known along the direction parallel to the slit and orthogonal to its axis. The smaller this uncertainty, the larger the uncertainty on the momentum of the quantum in that direction. A larger uncertainty in this momentum in turn means that the beam spreads over an area of the screen which is larger in that direction, building in this way a wider maximum. Again, the present setup allows to see different instances of this phenomenon at once.

From a more conceptual side, this continuous transition from ray to wave seems, when transposed to the quantum realm, to contradict the dichotomic particle-wave nature which is considered to be one of the cornerstones of quantum mechanics. In fact, when in 1909 Einstein first introduced the 'particle-wave dualism principle' for light [9], he suggested that photons exhibit either wave-like or particle-like behaviour depending on specific conditions. This principle was in 1927 subsumed in Bohr's 'Complementarity principle' [10, 11], asserting that the descriptions of quantum entities as waves or particles are complementary and dependent on the measuring instrument used. According to this formulation, the particle and wave aspects cannot coexist simultaneously: any attempt to observe one aspect precludes the observation of the other. However, over the years several authors found this dualistic nature to be both unphysical and complex. In the Eighties, Greenberger and Yasin [12] proposed a formulation of complementarity according to which a quantum system can simultaneously exhibit both particle-like and wavelike behaviour. Complementarity manifests then in the fact that a stronger manifestation of the wave-like nature implies a weaker manifestation of the particle-like nature, and vice versa. In this formulation, the wave-like and particle-like natures are not mutually exclusive but can intertwine. In the experiments described above, the intermediate regions between the Fraunhofer regime and the geometric optics regime correspond, when transposed to the quantum realm, to a situation in which quanta exhibit a behaviour which is intermediate between that of waves and that of particles.

2. The experimental setup

The experimental setup is shown in figure 2. The red diode laser beam has a nominal wavelength of $l = 630 \pm 20$ nm. The beam expander consists of a lens with a focal length of $+5.0$ cm (at 5 cm from the diode laser) so that the final transmitted beam is expanded in diameter to be bigger than the slit used in our experiments and is almost (but not perfectly) collimated. The expanded beam is incident on the slit, which is V-shaped, with a slit width ranging from 0 to 2 mm. The diffraction pattern is then acquired as an image using the smartphone camera. The experimental results are analysed with the aid of a digital camera and the ImageJ application [13] and are compared with the result of classical computations of the light intensity patterns performed using wave and ray optics.

3. Experimental results

In this phase, the measurements are made starting from a single photograph (cf figure 3 left) where the diffraction patterns thus obtained is shown. The results of the measurements, obtained by analysing the photo with ImageJ, are reported in figure 3 (right) and are in good agreement with the expected dependence of the distance between minima on the inverse of the width. In particular, figure 4 depicts the half-width of the central diffraction peak (measured both on the left and on the right) for different slit widths, and their comparisons with the theoretical results obtained from wave optics (continuous line) and from ray optics (dashed line) [9] respectively. A good agreement between theory and experiment can be observed in the full range, with a slightly worse result in a small interval around the intersection of the two curves, where of course neither the Fraunhofer approximation nor the geometric optics approximation are valid. The existence of two different regimes, a wave and a ray one, is clearly inferred.

The non perfect collimation of the beam implies that the image on the screen is a bit larger than what it would have been for a perfectly collimated beam by a certain constant factor. To estimate this factor, the measurements have been repeated varying the distance L between the screen and the slit. In this way, the images on the

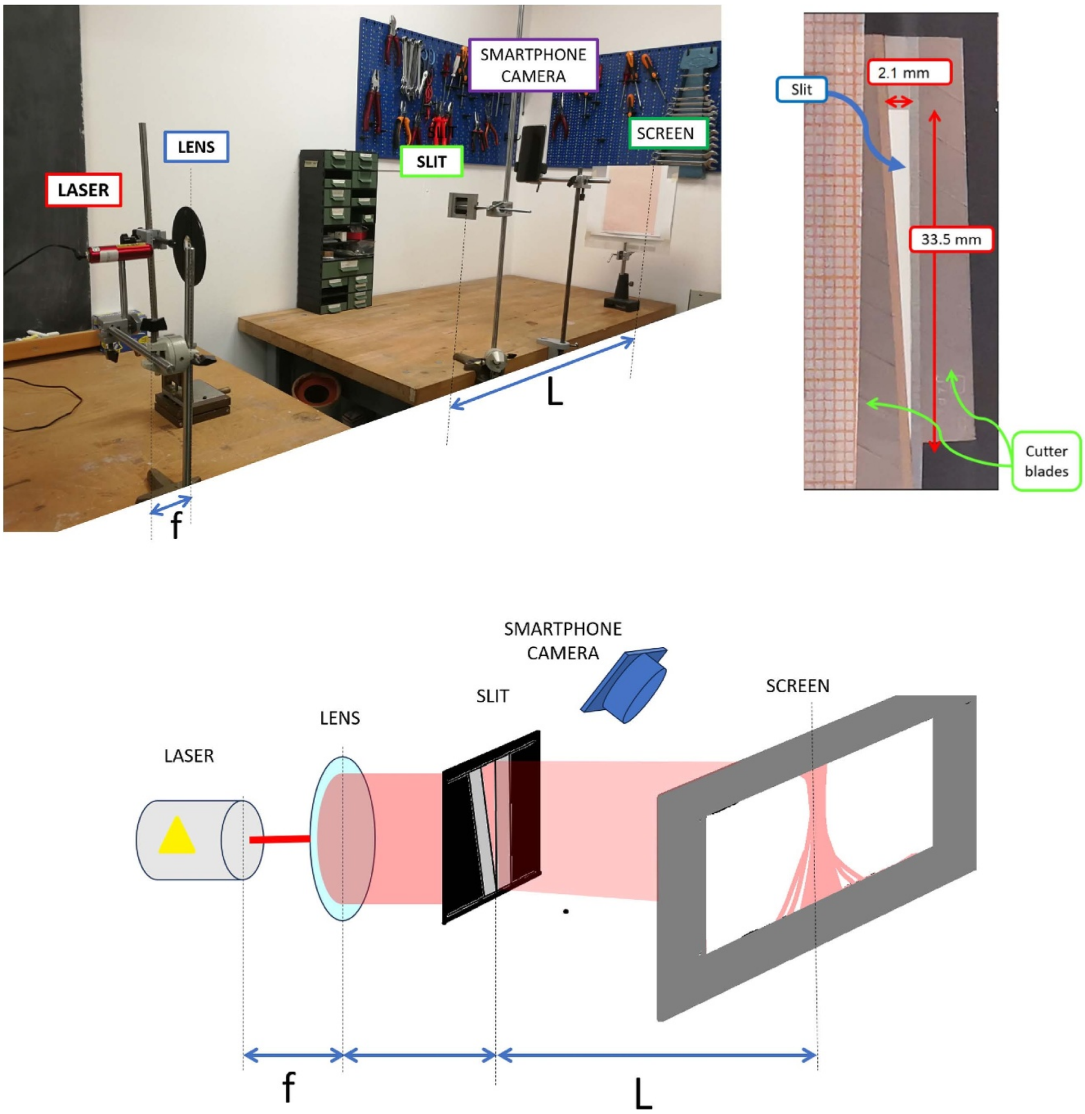


Figure 2. (Top left) A photo of the experimental set up. (Top right) The V shaped slit made of two cutter blades with the measures of its maximum width and of its height. The cutter blade are glued to a black cardboard on which an opening has been made. (Bottom) A schematic view of the experimental apparatus.

screen of the geometric optics image change, as shown in figure 5, left. In particular, the top width w of the image on the screen varies linearly with L: $w = w_0(1+sL)$, where $w_0 = 2.1$ mm is the true width of the slit. As shown in figure 5, right, with a linear fit we can determine for the scale factor the value $s = 0.001$ mm^{-1}. The straight line describing the image half-width as a function of the slit width in the geometric optics regime will obey the following $L-$dependent equation:

$$\frac{\delta}{2} = \frac{w}{2} = \frac{w_0}{2}(1+sL). \tag{1}$$

In the same way, in the wave regime the half-width will be described by the equation [7, 8]:

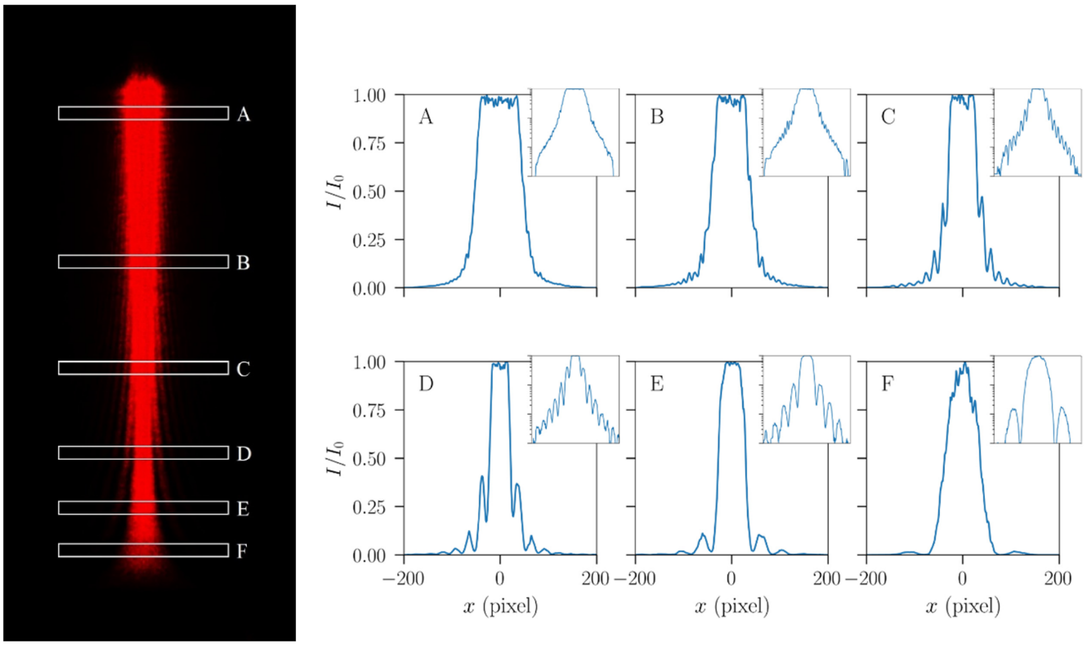


Figure 3. (Left) Picture of the light pattern on the screen and (right) normalized measurements of the intensities obtained with gamma correction of 1.8. In the inserts the same measurements are reported in semi-logarithmic scale in order to highlight the presence of the peaks and their width.

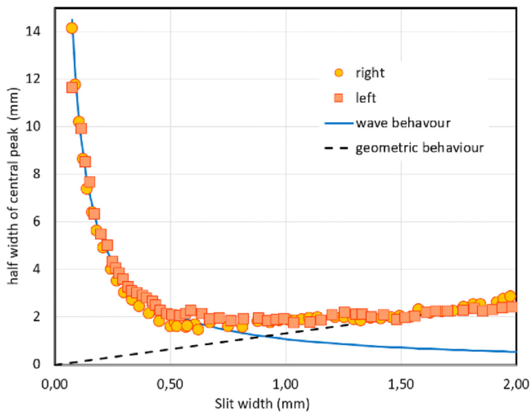


Figure 4. Experimental values of the half-width $\frac{\delta}{2}$ of the central peak (orange dots are used for left measurements and pink squares for left measurements) as a function of the measured slit size w. The horizontal and vertical uncertainties in the data are on the order of the size of the dots. The blue curve is a plot according to equation (2) below, the dashed line is a plot of the geometric optics prediction according to equation (1) below. The distance between the slit and the screen is $L = 1900$ mm. The transition from the Fraunhofer to the geometric optics regime should occur near a critical slit width given by equation (3) below, which appears to be confirmed with an uncertainty of about 20%.

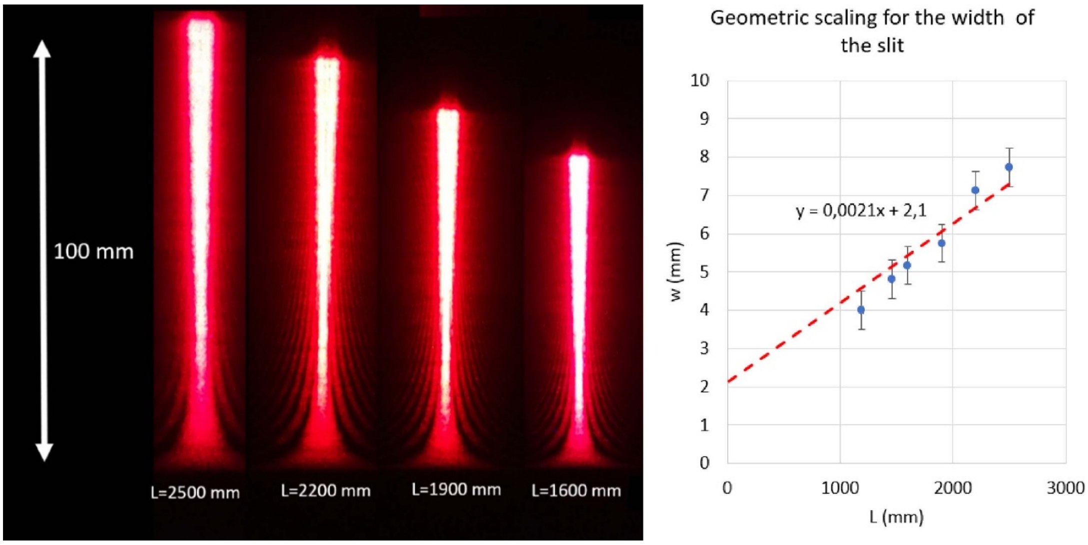


Figure 5. (Left) Images of the slit obtained for different values of the distance L between the slit and the screen, showing the scale variations. The scale factor $s = 0.0013\ \mathrm{mm}^{-1}$ is obtained dividing the slope of the straight line by the length of the slit (33.5 mm). (Right) The linear fit.

$$\frac{\delta}{2} = \frac{K}{w_0} = \frac{\lambda L}{w_0}. \tag{2}$$

From equations (1) and (2) we get the 'critical' value at which the two curves intersect:

$$w_{0c} = \sqrt{\frac{2\lambda L}{(1+sL)}} \sim 0.9\ \mathrm{mm}, \tag{3}$$

which, as we saw from figure 4, is in good agreement with our measurements.

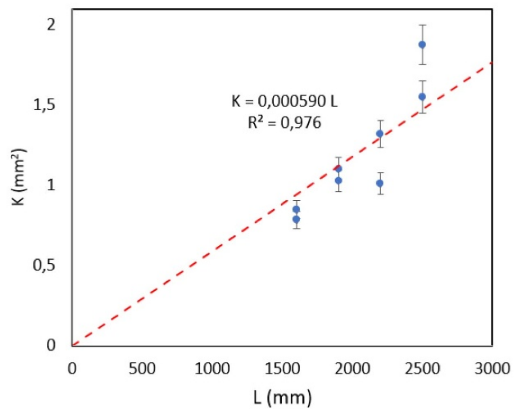
We also performed a second set of measurements, in which the half-widths $\frac{\delta}{2}$ of the maxima have been measured directly on the picture (by measuring the positions of the minima on the left and on the right) case-by-case for the various values of the distance L. The corresponding effective values of the slit widths (again to take into account the non-perfect collimation of the beam) have been obtained as $w = sLw_0$ with $w_0 = 2.1 \pm 0.1$ mm. Since $\frac{\delta}{2}$ and w_0 should be in inverse linear relation in the wave regime, inverting it we expect the following linear relation to hold:

$$\frac{2}{\delta} = q_L\, w_0 \rightarrow q_L = \frac{1}{K} = \frac{1}{\lambda L}. \tag{4}$$

From this relation, we can extract the values of K corresponding to the different values of L, and thus get a measure of the laser wavelength λ. Figure 6 (right) shows the values of the quantity K as a function of the distance L (notice that for each value of L we have two values of $\frac{\delta}{2}$ and hence of K, measured on the left and on the right respectively). While the single values of K reported in the table in figure 6 (left) correspond to poorly accurate values of wavelength, their average is quite close to the nominal value. Also, the results of the linear fit show a good agreement with the nominal value of the wavelength. Thus, two different ways of computing λ form the same data give results in good agreement with the nominal value and among themselves.

L (mm)	$\lambda(nm)$	$\Delta\lambda(nm)$	K (mm^2)
2500	750	50	1,9
2200	600	60	1,3
1900	540	20	1,0
1600	490	20	0,78
2500	620	80	1,6
2200	460	30	1,01
1900	580	30	1,10
1600	530	10	0,89

$\lambda = 570\,nm \quad \Delta\lambda = 90\,nm$



$\lambda = 590$ nm $\quad \Delta\lambda = 40\,nm$

Figure 6. (Left) Table of the values of K obtained for different values of L, and of the corresponding values and uncertainties for the wavelength. Below the table the average wavelength with its error, given by the standard deviation, is reported. (Right) Plot of the values of K as a function of L and the linear fit with the result and uncertainty for the wavelength.

4. Conclusions

In this paper we have described a quantitative optical experiment which can be performed with easily retrievable material, and clearly displays the crossover from the wave optics to the geometric optics regime all at once, without expensive equipment. The experiment can be also used to exemplify some important aspects of quantum mechanics, most notably the transition from 'quantum' to 'classical' behaviour, and also the uncertainty principle, and as such it is suitable to be included in an experiment-oriented teaching-learning sequence designed to teach the elements of quantum physics. The experiment has been included in an experiment-oriented teaching-learning sequence on quantum physics, dedicated to master students in mathematics and physics who aim at becoming high school teachers.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare no conflict of interest.

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