Matura thesis of Meinrad Sidler, 6d
Department of Physics
Kantonsschule Sursee

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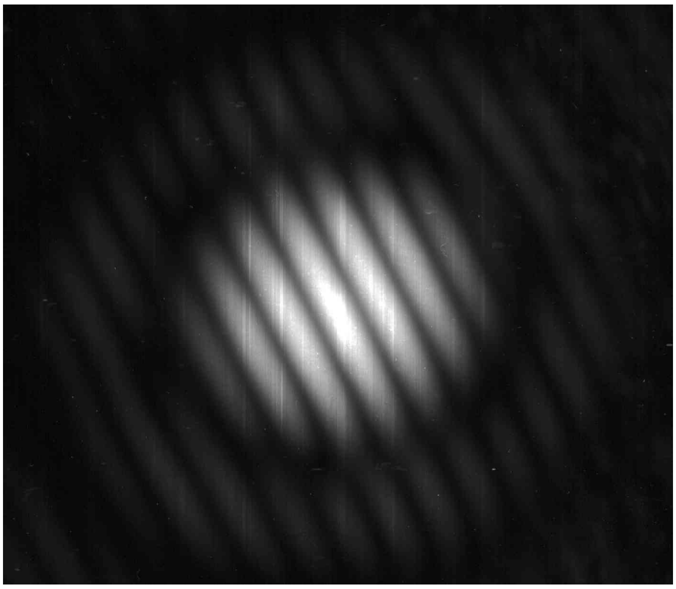
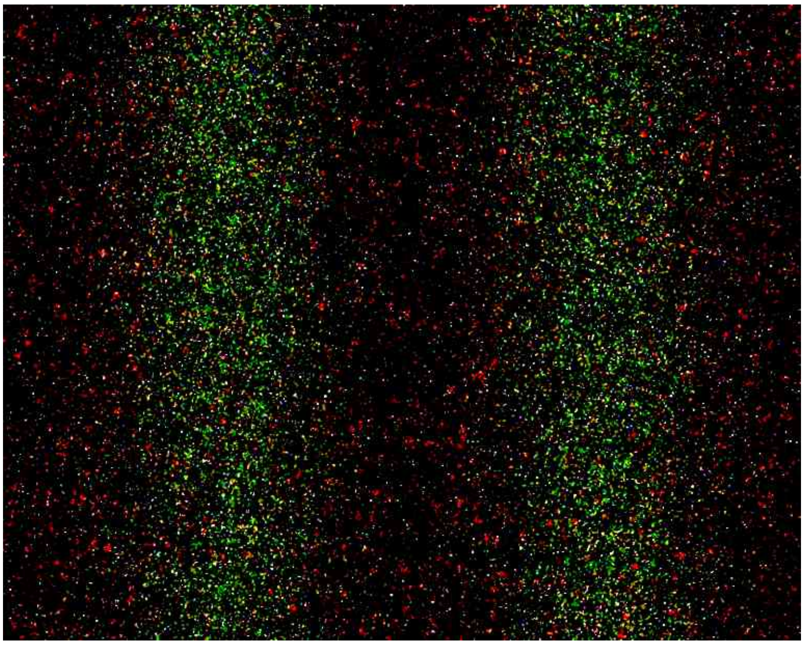


Waves and Quanta



Author:
Meinrad Sidler
Badhus 3a
6022 Grosswangen

Supervisor:
Dr. Jerzy Sromicki
Kirchstrasse 9
8107 Buchs ZH

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I Introduction

Light is perhaps the most fundamental object in Nature. It is a condition of life. That's why already in the 6^{th} century BC Indians made theories of light. Later, scientists hardly ever agreed on theories of light. The reason is that many of the physical phenomena in which light is involved can be explained by two extreme theories of light: corpuscular- or the wave model.

Our experience from the sunlight breaking through during the foggy days in the forest suggests that the light spreads as straight-lined so called "rays". Here the idea of light particles (corpuscles) was born. For simple applications this geometrical model of light is sufficient.

However, the corpuscular model doesn't explain more complex effects such as diffraction or interference. Such behavior of light can be very successfully described by the wave model.
In everyday life we don't really ask ourselves why we can listen to the radio or use mobile phones even when they don't seem to have any physical connection to the radio station. In fact, the electromagnetic waves, which have great similarity to light, are used to transmit the signals between the radio station and the receivers.

The purpose of this work is experimental investigation of light phenomena. My biggest interest is the wave-particle duality which is the central part of quantum theory. I will provide experimental data in favor of the two extreme models of light and I will discuss some theoretical aspects. The maths of waves is fascinating however, I restrict its discussion to the minimum which is necessary to illustrate physical principles. The real challenge of this work was to perform careful experiments with very modest, generally available equipment (chapter III.2). Although I focused on the physical content of the images I was surprised and fascinated by their esthetic beauty. This motivated me for continuous improvements and development of my experiments.

II Theoretical foundations

1 History

As mentioned above, in the 17^{th} and 18^{th} century, there were two different models to explain the behavior of light. The corpuscular model was promoted by Sir I. Newton. His idea was that light consists of many little particles moving as "rays" on straight lines. In contrast, Ch. Huygens's theory was that light is a wave. Both models are equally successful in explaining propagation, reflection and refraction of light. It was only because of Newton's immense authority that his model was generally accepted.

On the break of $18^{th}/19^{th}$ century, the situation changed. An English scientist T. Young made a crucial experiment in which he "overlapped" two rays. On the screen he saw a special pattern resembling the interference phenomena, which were well known from observations of waves on the water. From that moment on, the wave model of light became again more popular. In fact, it was superior to the particle model since it could explain the broader class of phenomena.

This hasn't changed much until Albert Einstein explained the photoelectric effect. His explanation to this phenomenon was one of the first steps towards the wave-particle duality[1]. Nowadays, the quantum physics is successful in explaining that light behaves like particles when it interacts with other particles of matter; however, propagation of light exhibits its wave properties.

[1] Detailed discussion follows in chapter 4

2 The wave model of light

2.1 Interferences

Light belongs to the class of electromagnetic waves. The complete theory of electromagnetic phenomena was developed by J. C. Maxwell. His "Treatise on Electricity and Magnetism" (1873) was a major step in understanding the nature of all electromagnetic effects. A direct consequence of the linearity of "Maxwell's Equations" is a superposition principle, according to which the wave amplitudes are added. The simplified wave theory of light, which is sufficient for further discussion here, was developed before Maxwell by A.J. Fresnel and J. Fraunhofer.

To demonstrate the main physical principles of interference a simplest case of the two slit experiment will be discussed.

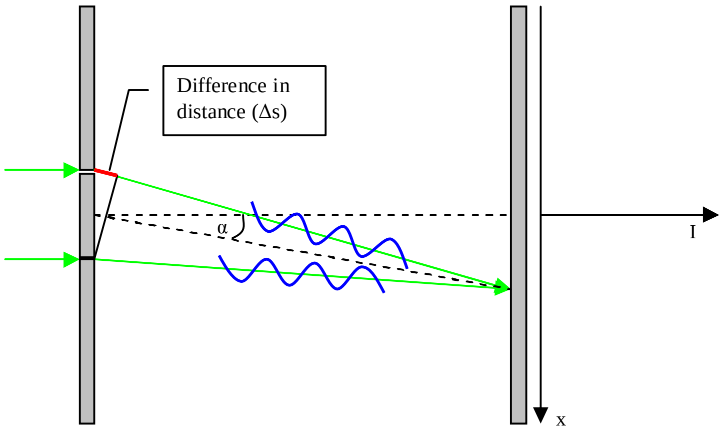


***Fig. 1:** Double-slit experiment*
The interference results from the different distances from the two slits to a certain point on the screen. The difference in distance is represented by the variable Δs. If Δs modulo λ is 0 than the maximal amplitude and intensity is observed on the screen (constructive interference). If Δs modulo λ=1/2 then no intensity is observed (destructive interference).

Because of the superposition principle (addition of amplitudes), the contributing waves are able to enforce or neutralize each other. In extreme cases, the maxima and minima of the wave amplitudes and resulting intensities arise (see Fig. 1).

The difference in distance is: $\Delta s = d \cdot \sin(\alpha)$

Local maxima of intensity are observed at: $\Delta s = n \cdot \gamma$

Local minima of intensity are observed at: $\Delta s = \left(n + \frac{1}{2}\right) \cdot \gamma$

A particularly efficient simplification is to consider the screen to be infinitively far from the slit. In this case α is very close to zero and the small-angle-approximation is precise enough. As a consequence of this sin(α) can be replaced by α in radian.

$$\Delta s \approx d \cdot \alpha$$

It follows for the positions of the maxima and minima, respectively:

$$\alpha_{\max} \approx \frac{n \cdot \lambda}{d}, \qquad \alpha_{\min} \approx \frac{(n+1/2) \cdot \lambda}{d}$$

We note that the angular distance between the fringes (the maxima of amplitudes) increases the smaller the distance between the slits is. I will use this feature in my experiments.

The case of single-gap is obviously more complicated. The idea is to treat a gap as an infinite number of wave sources. Mathematical treatment requires integral over the gap. This procedure is more complex, however the results are available in standard textbooks [2]. The formulas for the position of the minima and maxima are the same as given above. The most interesting, however, is the intensity distribution of the light on the screen. Again, the Fraunhofer approximation is used. The final formulas that describe the intensity in dependence of the angle α behind a single gap are:

$$I(\alpha) = I_0 \left(\frac{\sin(\varphi/2)}{\varphi/2} \right)^2, \quad \varphi \text{ is the difference of phase of the two edge rays}$$

$$\varphi = 2\pi \cdot \frac{\Delta s}{\lambda}, \qquad \Delta s = d \cdot \sin(\alpha)$$

$$\varphi = 2\pi \frac{d \cdot \sin(\alpha)}{\lambda}, \qquad \alpha << \pi \ , \quad \sin(\alpha) \approx \alpha \quad \text{(in radian)}$$

$$I(\alpha) = I_0 \frac{\sin^2\left(\pi \frac{d}{\lambda} \alpha \right)}{\left(\pi \frac{d}{\lambda} \alpha \right)^2}$$

To get the intensity behind a double-gap, one has to multiply the term $I(\alpha)$ with $\cos^2\left(2 \cdot \pi \cdot \frac{D}{\lambda} \alpha \right)$

2.2 Polarization

Waves in general are defined by three attributes: intensity, frequency and polarization. A wave is linearly polarized if the oscillations of the whole medium take place in a particularly distinguished plane. Only the transverse waves exhibit the polarization phenomena. The light wave is characterized by the oscillations of the electrical field-vector, which are perpendicular to the direction of propagation. Although also so-called circular polarization is possible the laser light is usually linearly polarized. The degree of polarization is very high, and in most cases exceeds 99%.

Polarizer is a simple device which transmits only one component of the electric field of the incoming wave. Efficient polarizer for visible light are produced by evaporating long chains of hydrocarbons on a thin foil and stretching the foil along one direction[3].

[2] Crawford, Frank S.: „Schwingungen und Wellen“, 1974, Berkeley Physik Kurs Vol. 3, Vieweg & Sohn Braunschweig, Wiesbaden
[3] Patent, Polaroid ®

3 The particle model of light

3.1 The photo-effect

If a negative ionized plate of metal is hit by ultraviolet light, the charge of the plate is neutralized while the plate would keep its charge unchanged if exposed to the light of lower frequencies. The wave theory of light fails totally in explanation of this effect. However, the reinvented by A. Einstein (1905) particle model of light provides a very simple explanation of this so-called photoelectric effect. The absorption of light appears in a single step: the light-particle (γ-photon) disappears and its whole energy is overtaken by a single electron.

$E_e = E_\gamma - W$

E_e : kinetic energy of an electron after leaving the plate

E_γ : energy of the photon which hits the electron

W : potential energy of an electron necessary to leave the plate

According to Einstein's hypothesis the energy of photon and the frequency of light are related by:

$E_\gamma = h \cdot f$, with Planck's constant h h and the frequency of the photon f

The formulas above allow for calculation of the minimum frequency that is necessary for a photon to "eject" an electron.

$$E_\gamma \geq W$$

$$f \geq \frac{W}{h}$$

W is a material-specific constant in the order of eV. For example, the W of iron is much higher than the W of Silicon. Digital cameras contain a CCD (Charge-Coupled Device) which basically consists of a segmented silicon plate with an advanced readout technique. The photons which hit the CCD eject electrons from a particular element (so-called pixel) of the CCD plate. The lost charge is measured and digitized into the brightness value. In brief, digital cameras, which are my main measuring instrument, rely on the photoelectric effect. In fact, each digital photography provides therefore an evidence for the particle model of light.

4 The quantum nature model of light

4.1 Duality

We note that light can't entirely be explained by one of the two extreme models. In order to prevent any conflicts between the two theories quantum physics is successful in explaining that light is not just *either* a wave *or* a particle but it behaves under certain conditions like an ensemble of particles and under other conditions like a wave. In particular: when the light interacts with other particles of matter, it behaves like corpuscles. On the other hand, light exhibits its wave properties when it propagates in space. In addition, such dual properties or not only restricted to light but are valid for material particles as well.

Recent experiments have demonstrated the wave-particle duality for as heavy and complex particles as the C-60 fullerene molecules[4].

[4] A. Zeilinger, University of Wien, 2000-

4.2 Coherence length

Assuming that a light source produces monochromatic in-phase waves, the coherence length is defined as the distance between the source and the point where the difference in phase reaches the level where the contrast between the maxima and the minima in case of interference is 50%.

We note that the contrast between maximum and minimum depends on the distance between the aperture and the screen divided by the coherence length of the light source.

In quantum physics, the coherence length is the distance at which the photon acts as a wave.

4.3 A single photon in front of a double-hole

The double-slit experiment is easy explained by the wave model of light. However, in case of very low intensity passing the slits, the particle model of light has to be considered.

What happens to a single photon that passes the double slit? What should it interfere with if the distance to the next photon is further than the coherence length? Would there be an interference pattern if the exposure time were long enough?

These questions have motivated my experimental study.

4.4 Recent developments

Although the answer to the questions above is well known: “Yes, interferences are observed even with single photons”, the behavior of photons is still a mystery. In fact, in last two decades a new series of experiments with photons and atoms was developed[5] which not only readdress the questions above but go further in the investigations of principles of quantum mechanics. Some of these experiments have prospects of applications in the field of computer science and information technology (quantum cryptography, quantum computers, teleportation[5]).

[5] A. Aspect, a series of papers in Phys. Rev. Lett., 1982.
L. Mandel, University of Rochester.
O. Scully, R. Y. Chiao, University of California, Berkeley .
A. Zeilinger, University of Wien.

III Experimental part

1 Introduction

In general, I perform two kinds of experiments. The so-called high intensity experiments were done with use of the full laser's power. In contrast, the low intensity experiments were conducted with strongly attenuated laser beam. The purpose of the low intensity is to enter the regime were the quantum nature of light will be disclosed.

2 Equipment

The following equipment was used in the experiments:

- Lasers:
  1. 2x red laser pointer; 650nm; P<1mW ("MIgros", 30 CHF)
  2. 1x green laser pointer; 532nm; P<5mW ("Contraves", 150 CHF, school equipment)
- Filters:
  1. Polarizer ("Conatex", 10 CHF)
  2. Floppy disk ("MediaMarkt", 1 CHF)
- Camera:
  Canon EOS 350D; 8MPixel; CMOS-chip; chip size: 22.2x14.8mm ("Fust", 1200 CHF, school equipment)
- Scanner:
  Canon CanoScan LiDE 25 ("Steg", 70 CHF, family equipment)
- Black paper, "Scotch" tape, scissors (Papeterie "VonMatt", 10 CHF)

3 High intensity experiments

3.1 Measurements

The experiments were developed and the measurements were performed in June and September 2006. The June-measurements were made by taking pictures of the screen and with a scanner that was placed in the position of the screen. The scanner's cover was opened so that the light directly fell on the scanner's glass plate. The advantage of these experiments was that the intensity distribution was measured very precisely. In addition, there weren't any problems with stretch of the picture and the resolution was even higher than the one obtained by taking photographs of the screen with the camera. The disadvantage was that the lamp of the scanner lit the whole room. Its light was scattered by the walls of the darkroom producing an non-negligible level of background on pictures taken by the scanner. This was bad for the contrast.

Experimental arrangement

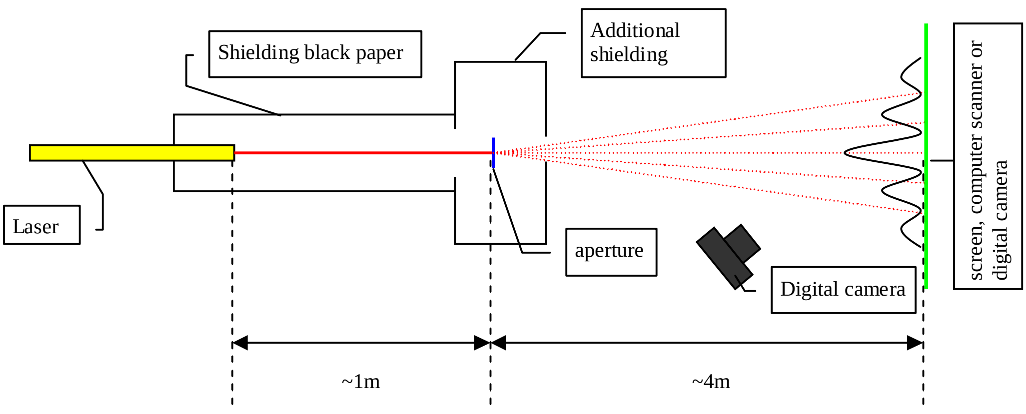


Fig. 2: *Experimental arrangement*

3.2 Single-hole experiments

The formula for the intensity distribution behind a one-dimensional single-gap was given in the section 2.1 of the theoretical part.
Although the mathematical treatment of holes is much more complicated, experiments with holes are easier. The holes in a black paper or a thin 0.2mm PVC-foils are easily produced by pins or needles. In contrast to slits, the images of holes are two-dimensional and the intensity is distributed over a large area. In addition, the images have higher degree of symmetry. Therefore, I will focus on the description of my experiments with holes. Although the mathematical expressions for the intensity distribution in case of holes are non-analytic the physical content is analogous to the gaps.

The results of the first experiments are presented below. The hole was illuminated by the laser beam and the diffraction pattern was taken.

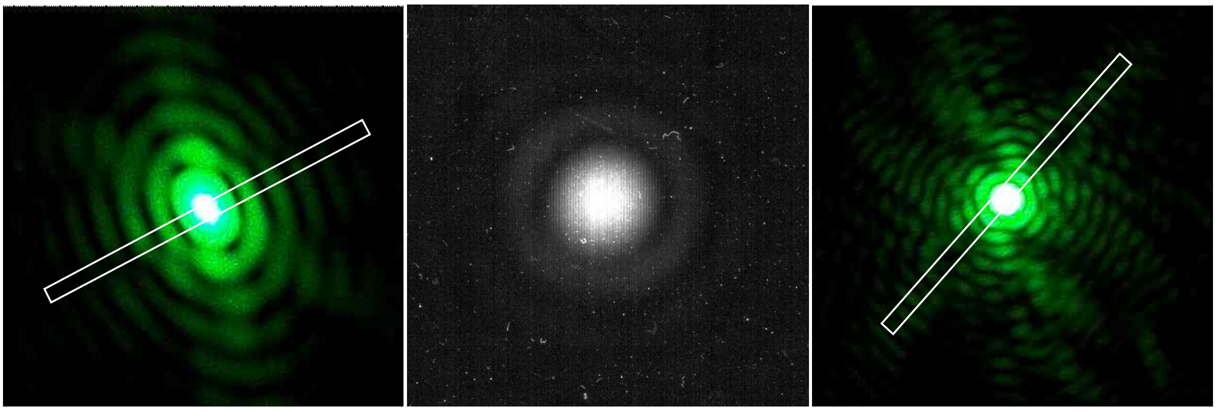


Fig. 3: *The first results*
Left: A diffraction pattern of an "elliptical" hole (ca. 0.3mm) taken from the paper-screen with the digital camera. Note that up the diffraction maxima up seventh order are visible.
Middle: A diffraction pattern on a very regular, small (ca. 0.1mm) round hole taken with a scanner.
Right: A diffraction pattern on an irregular, large (ca. 0.6mm) hole, again with the digital camera. Diffraction maxima up to 20th order are visible.
The boxes on the left and right were used for projections (see text).

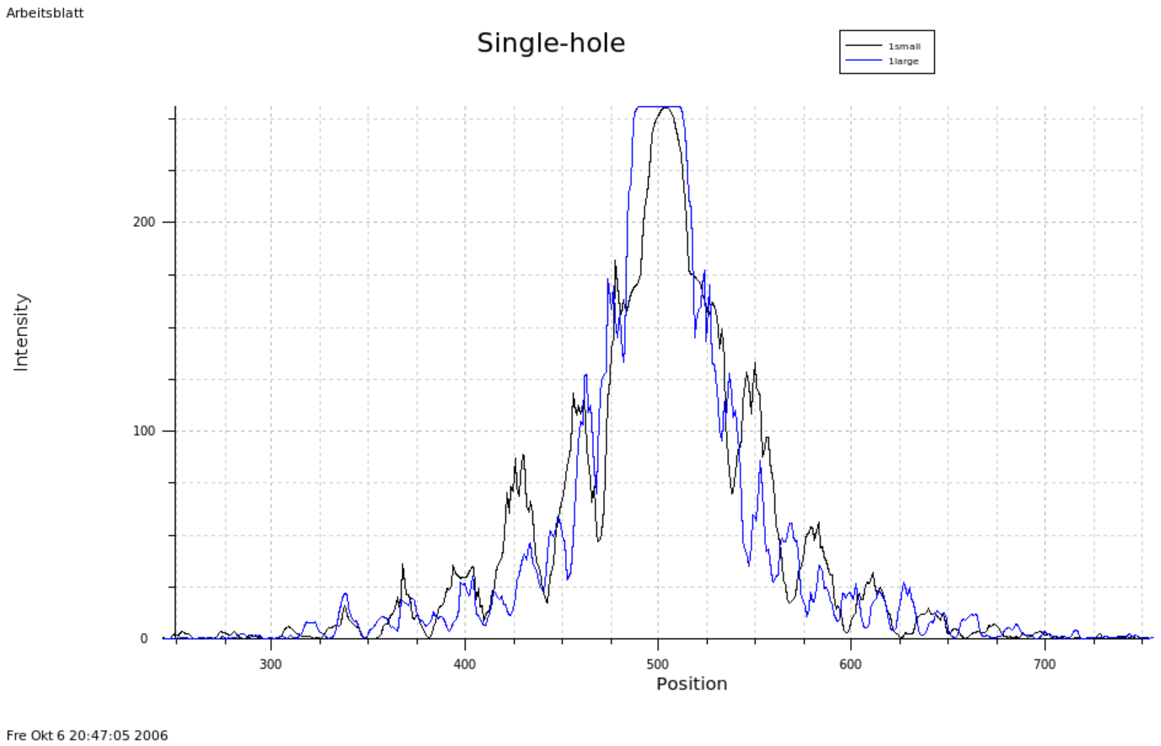
As already mentioned, the distance between the fringes is inversely proportional to the diameter of the diaphragm. This is well documented in ***Fig. 4***.

More quantitative analysis can be done with the aid of projections of intensities contained in the boxes shown in the ***Fig. 3***. This allows direct comparison of the distances between the fringes. The exact measurements of the hole diameters with the scanner were:

$$d_{left} = (0.29 \pm 0.02)\text{mm}$$
$$d_{right} = (0.59 \pm 0.02)\text{mm}$$

The ratio of these values amounts to 2.0±0.2.
The observed distance between the fringes (***Fig. 4***) is in fact twice as large for the first hole as for the second one.

The intensity hardly ever reaches the zero-level i.e.: the contrast between the intensity of a minimum and the intensity of a maximum is not great. A possible explanation is: The pattern was projected onto a screen of white paper and the picture of the screen was taken with the camera. There is a loss of quality because of the the partial transmission and scattering of the light in the paper.



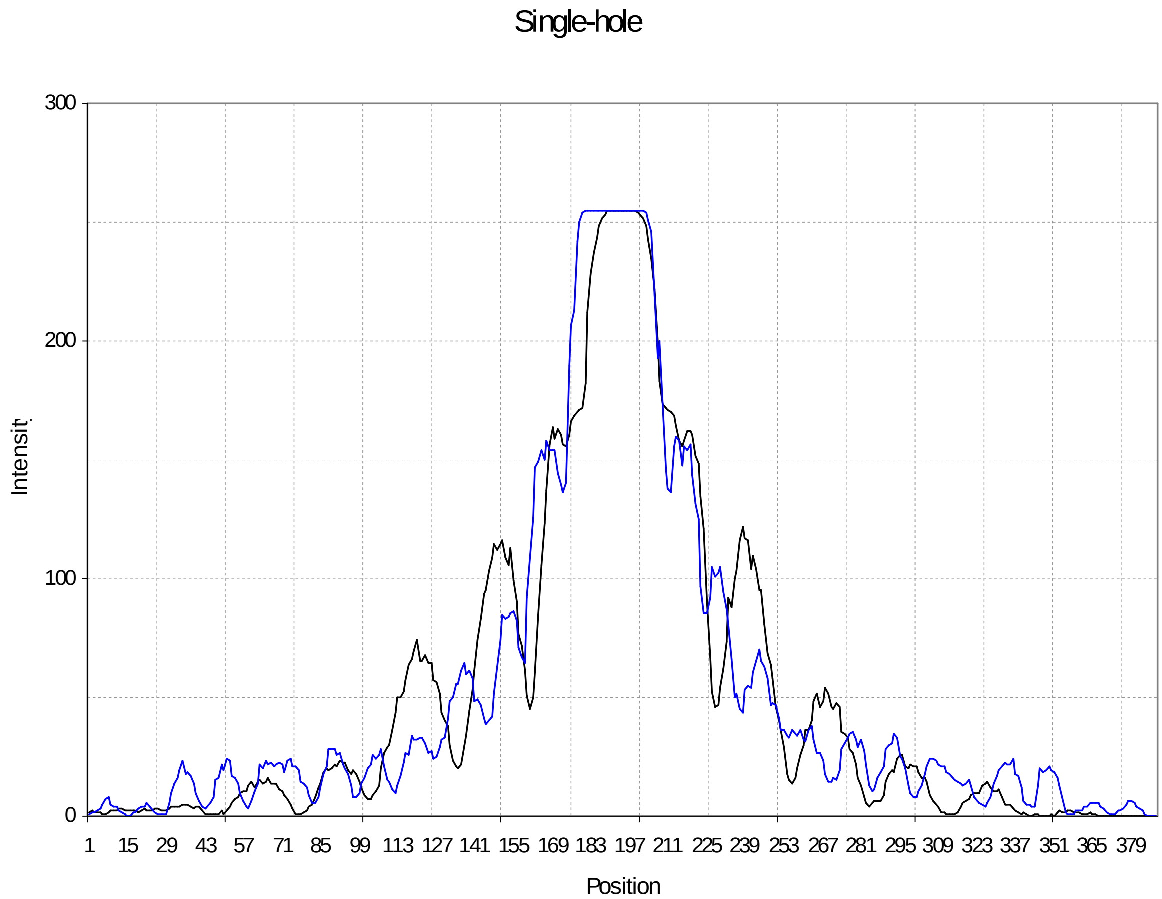


Fig. 4: *Projections for the left and the rights side of the data from* ***Fig. 9***
On the top: the histogram of only one line.
On the bottom: the histogram for the average of a box.
See text for discussion.

3.3 Double-hole experiments

The expectations of these experiments is that the cosinus like curve is inscribed into the envelope which is given by the diffraction pattern of the single hole. In order to test this I prepared two apertures one with two holes placed rather near and the other one with two holes that are placed apart. The results are shown in ***Fig. 5***.

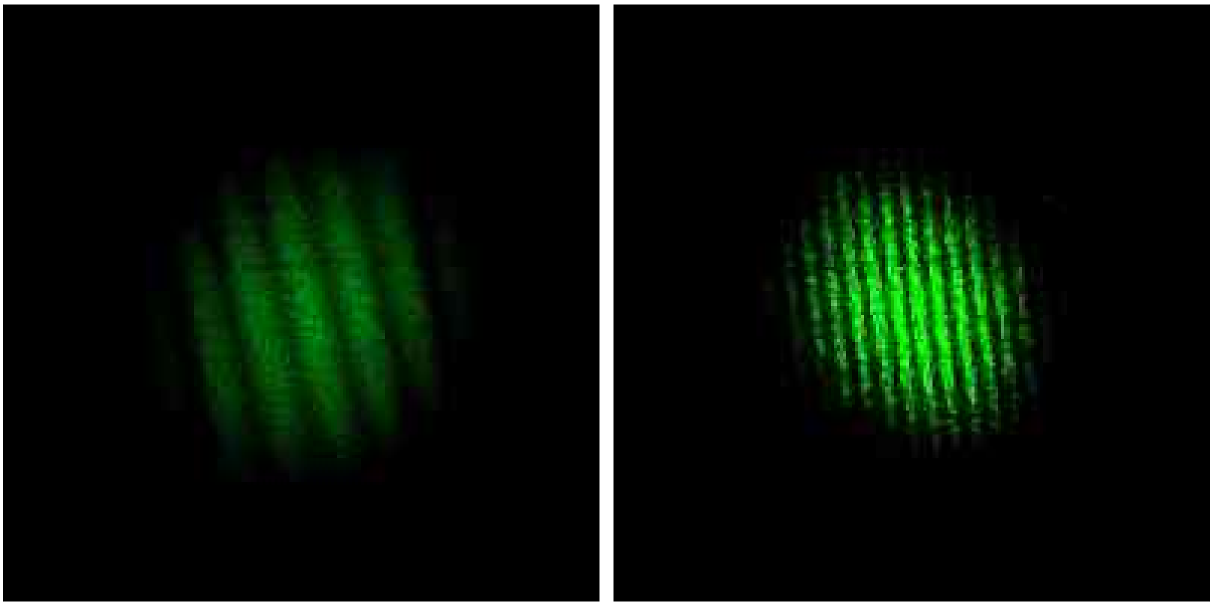


Fig. 5: *The results of double-hole experiments with similar diameters but distance is different by approximately factor of two.*
One notes that the density of fringes scales approximately by the ratio of distances.

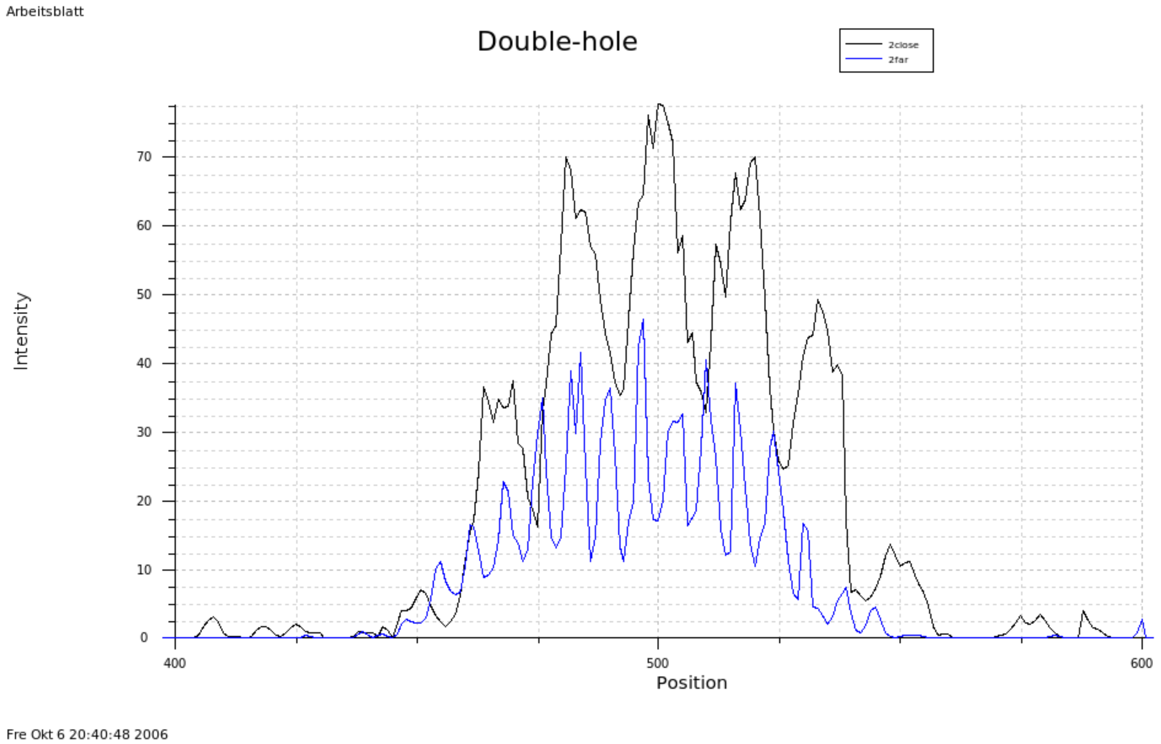


Fig. 6: *Projections for the double-hole experiments presented in the* ***Fig. 5***

3.4 Color

I pointed two lasers of different wavelengths on the same diaphragm. The aperture used was the same as in the ***Fig. 3,*** right. However, two lasers with the wavelengths of 532nm (green) and 650nm (red) were used. The results are shown in ***Fig. 8***.

Single-hole

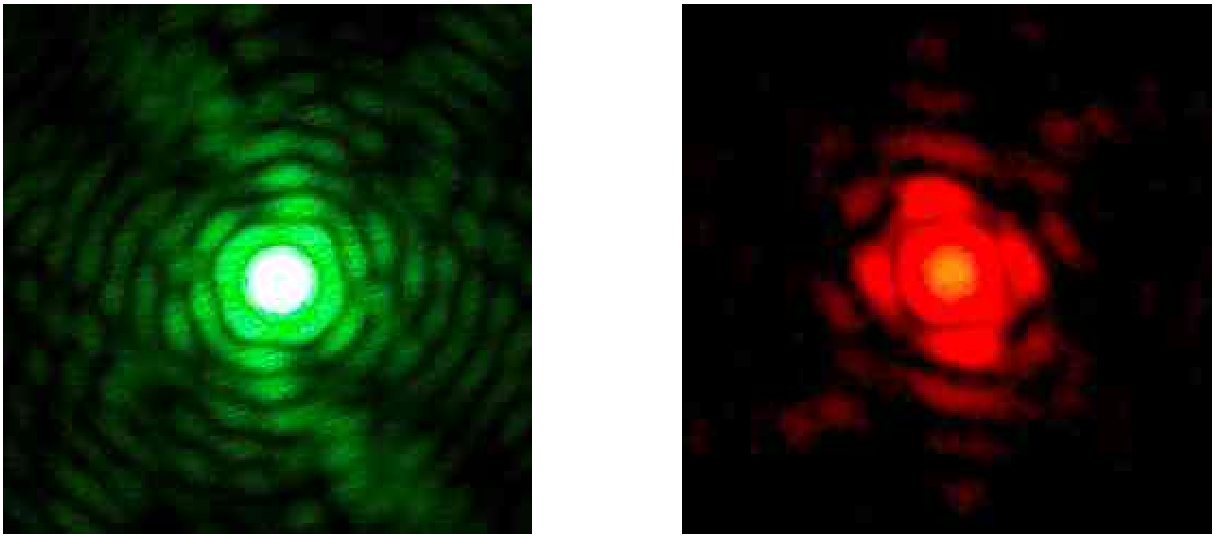


Fig. 7: *The diffraction patterns from the same hole illuminated by laser-light of two different wavelengths.*

The corresponding projections are shown in ***Fig. 8***.

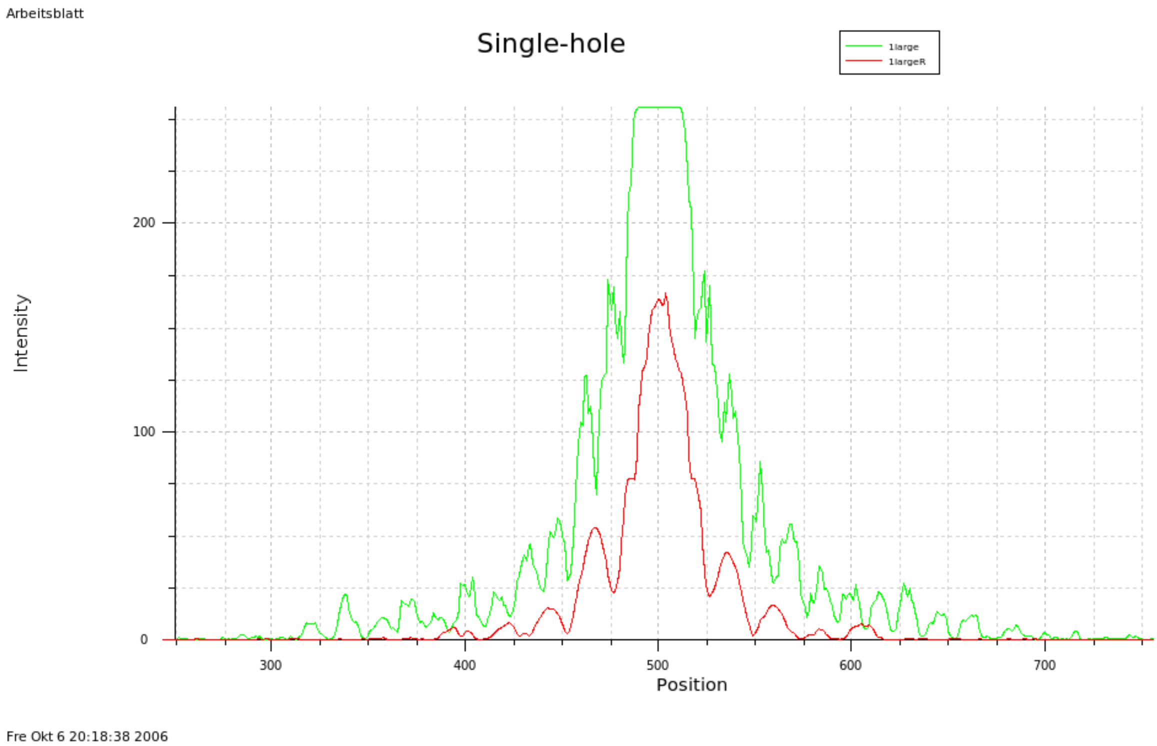


Fig. 8: *Projections of intensities using two-color data from* ***Fig. 7***.

The fringes of the green pattern should be

$$\frac{\lambda_{red}}{\lambda_{green}} = \frac{650nm}{532nm} \approx 1.22$$

times closer than those of the red pattern.

By counting the number of fringes between position 300 and 700 I obtained a factor of 1.21 which is almost exactly what I expected.

Similar experiments with two colors of light were performed also performed with double-holes. Again, all expectations are precisely confirmed.

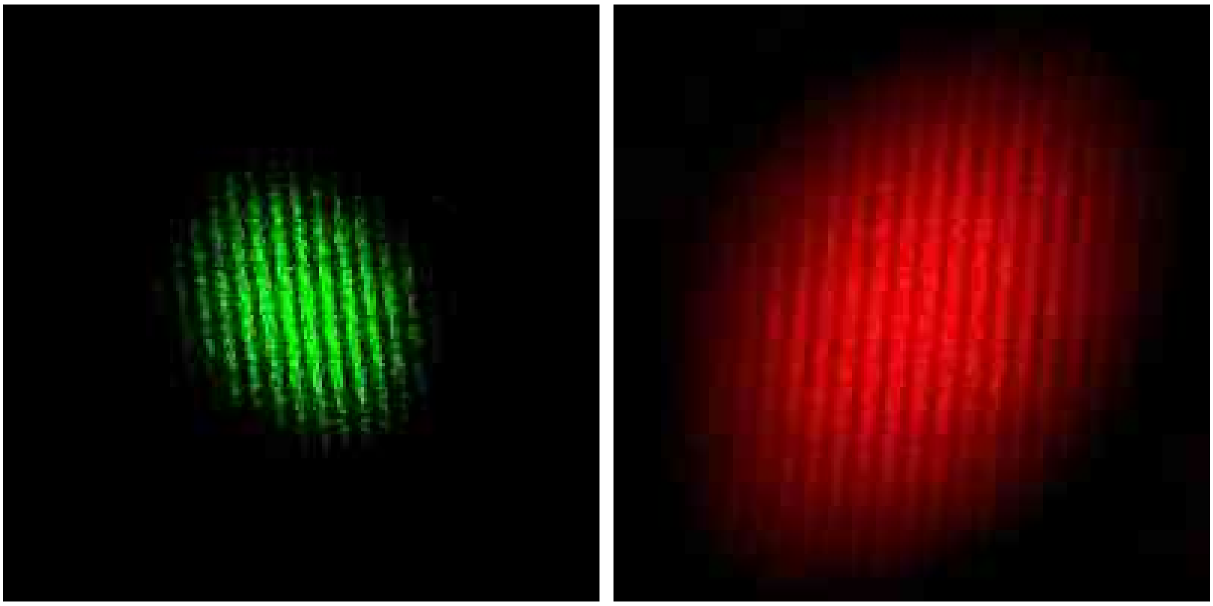


Fig. 9: *Two color experiments with interferences from double holes.*

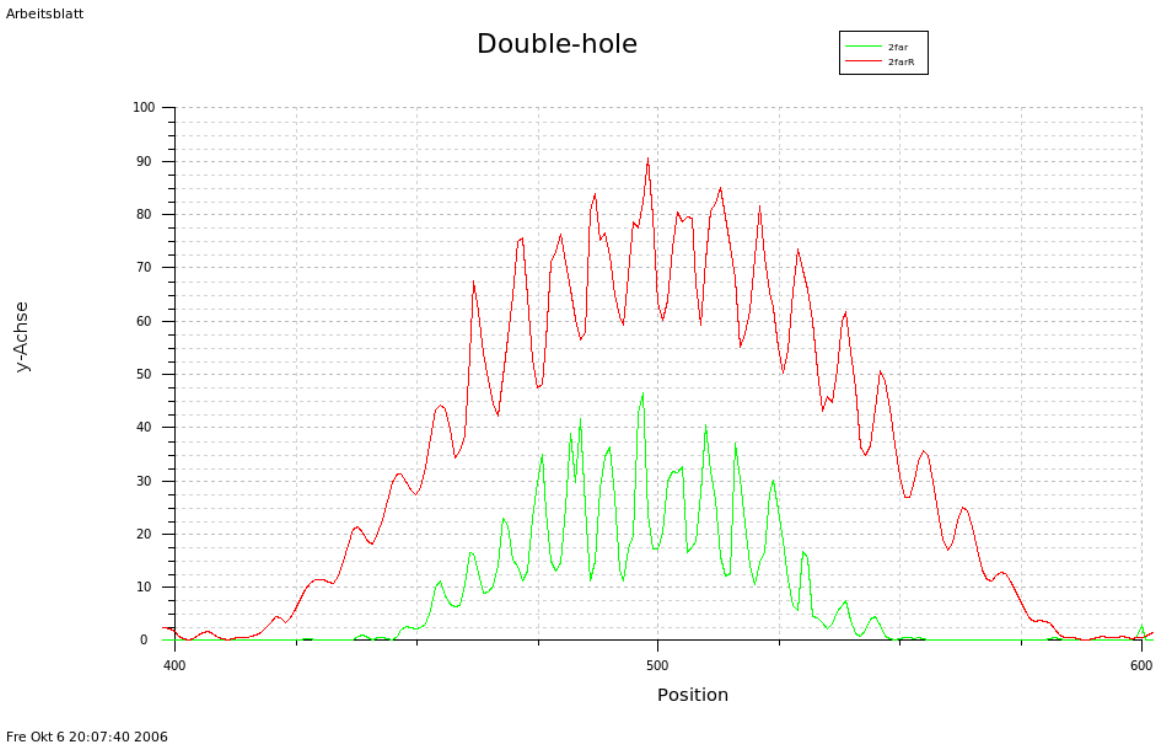


Fig. 10: *Projections corresponding for the data in* ***Fig. 9***

3.5 Further investigations

After discussion of the main physical effects in interference experiments, I present here more precise data which were obtained with improvements in shielding. All these pictures were taken with the scanner (black-and-white).

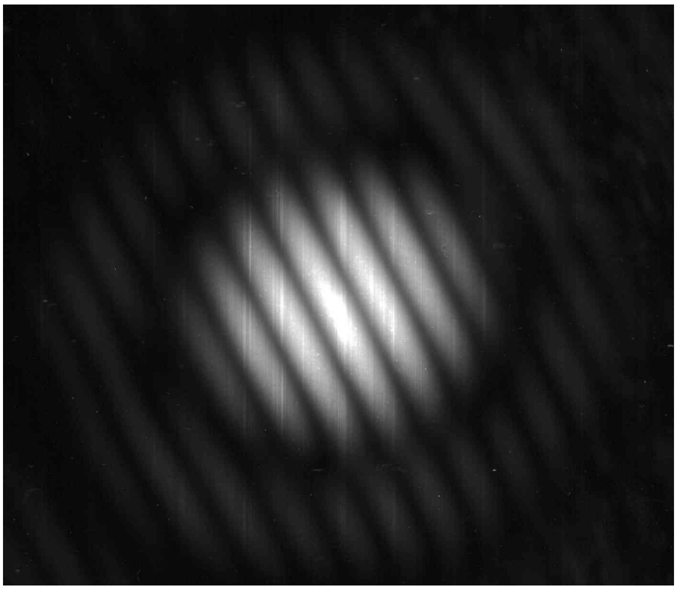


Fig. 11: *Double-hole (scale 1:1)*
This picture shows the interference pattern of a double hole arrangement. The holes are rather small and near. The consequence is that the fringes are well separated. We observe very nice interferences in the second order of the diffraction pattern.
The picture shows main advantages of the scanner as a measuring instrument: the contrast is very high and there the exposure is well balanced. In addition, the resolution of the picture is excellent even though the image was taken with a low-costs scanner (1200dpi).

The idea of the next experiment was to investigate a classical limit of interferences. Big holes (ca. 0.5mm) were used and the distance between was increased to approximately 1.5mm. The results are presented in ***Fig. 12***. The picture itself has a huge esthetical content, for example there are at least 10 diffraction maxima visible, but the physical meaning and the precision of the experiment are more important (see figure caption).

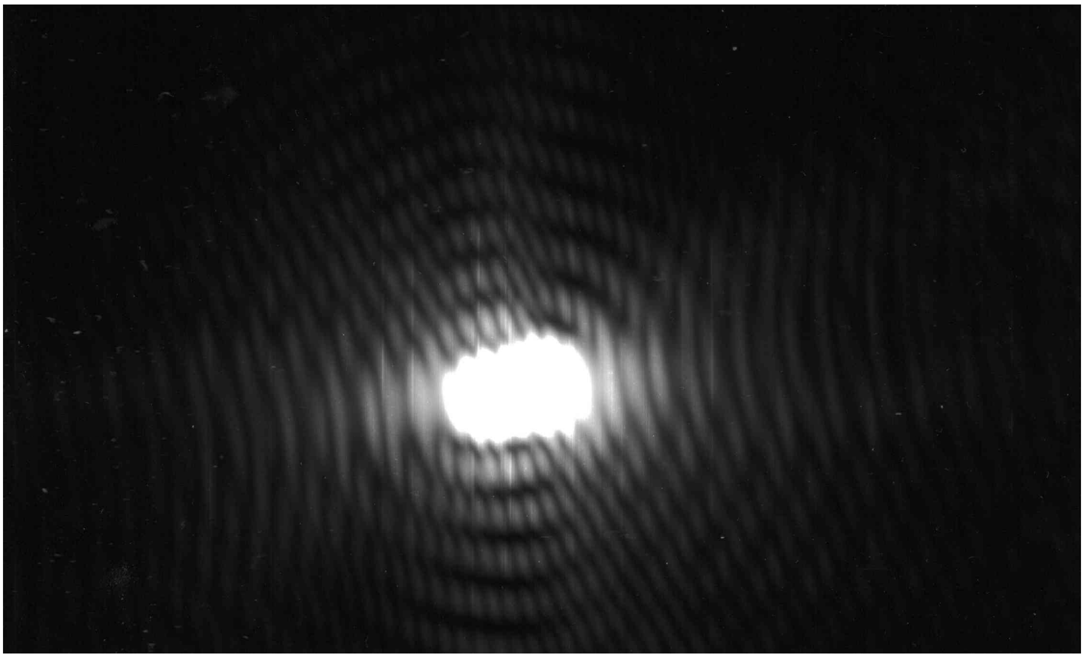
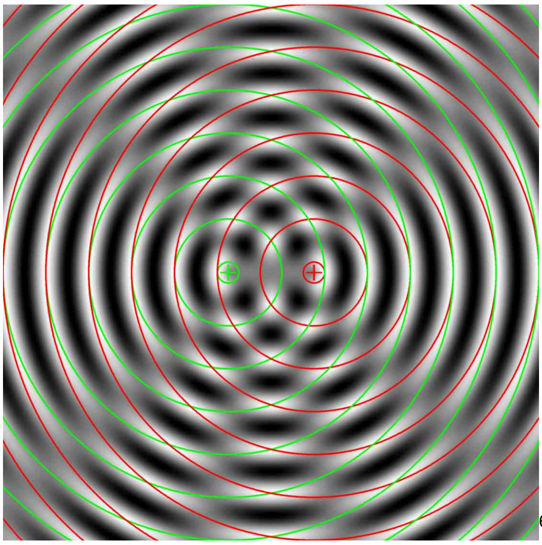


Fig. 12: *Double-hole (scale 1:1)*
This picture (in my opinion one of the most beautiful scans) shows the interference pattern behind an aperture with two large and far positioned holes. The fringes are rather close.
The image shows three classes of interferences. The first is the diffraction of the system of two holes responsible for the “rings”. The second interference is the one between the holes, which causes the “fringe-stripes”. The third one occurs only because the distance between the “rings” relative to the distance between the holes is exceedingly big.
The third grade interference can be made out the easiest by observing the angle of the “stripes” which changes in dependence of the horizontal distance to the central maximum.

A further detail: the far distance between the holes makes the central maximum look oval, which is clearly visible.

The following picture is a simulation of the interference of two circular waves.


[6]

[6] http://upload.wikimedia.org/wikipedia/commons/f/f1/Interferenz.jpg

3.6 *Polarization*

Very interesting experiments can be done with polarized light. I used linear polarizer described in the sections 2.2 and 3.2.First of all, in order to assure that the incoming light was always linearly polarized, a vertical polarization filter was placed directly at the exit of the laser. Further filters were sticked on in front of the holes. I present the obtained results with the corresponding descriptions in the figure captions.

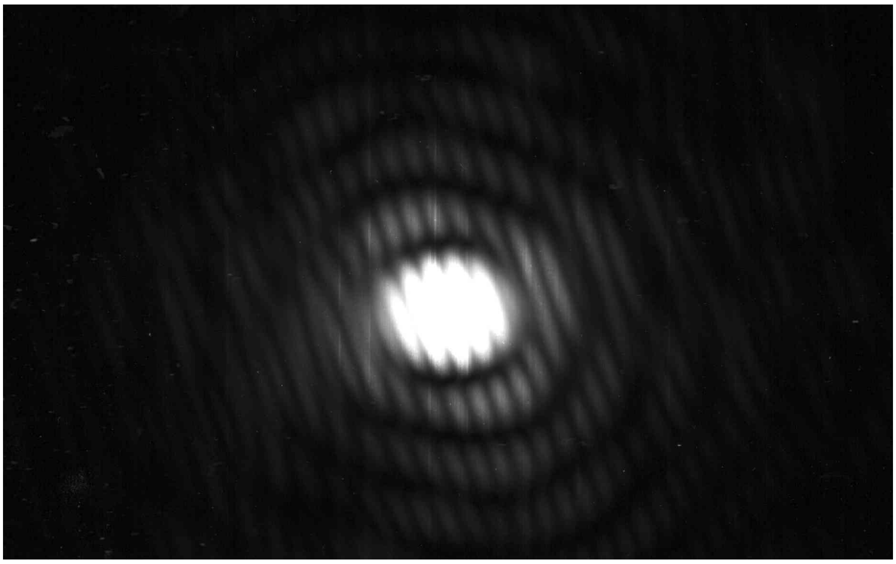


Fig. 13: *Double-hole (scale 1:1)*
This image shows the interference of a double hole. The main properties are similar to the ones of ***Fig. 12***. This photo was taken to compare with the next two images. Only one polarizer, at the exit of the laser, was used.

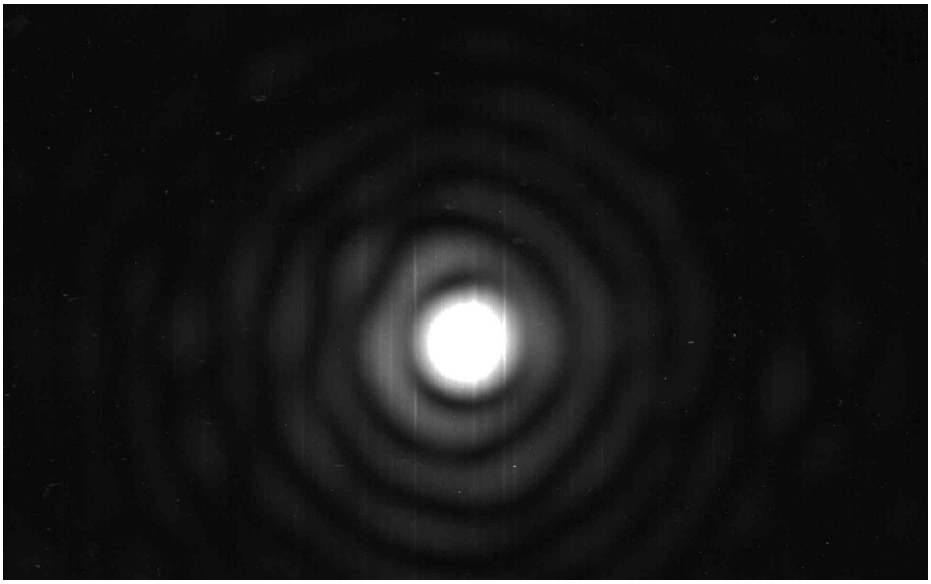


Fig. 14: *Double-hole with pre-selection* ***very important!***
The same aperture as above was used. The only difference compared to the picture above is that a polarizer as above is that polarizers were attached on both holes at the angles of ±45° with respect to the polarization of the light source.
The interferences have disappeared: two waves can't interfere if the angle between their polarization is 90° even if the holes are lit by the same point source of photons.
Compare to central part of ***Fig. 3***.

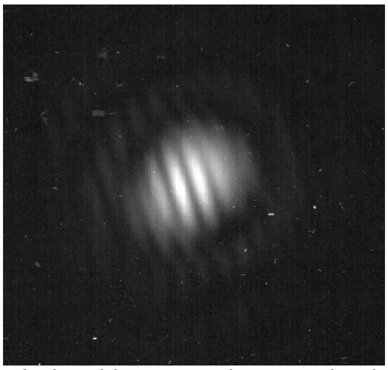


Fig. 15: *Double-hole with pre- and post-selection*
The experimental situation is the same: again, the same apertures as in the pictures on the previous page were used. However an additional laser at the angle of 90° with respect to the polarization of the light source was placed **after** the polarizers described in ***Fig. 14.***
The interferences reappear again. Surprise!?

3.7 Further investigations

I extended my investigations to a system of three holes. The results are presented below.

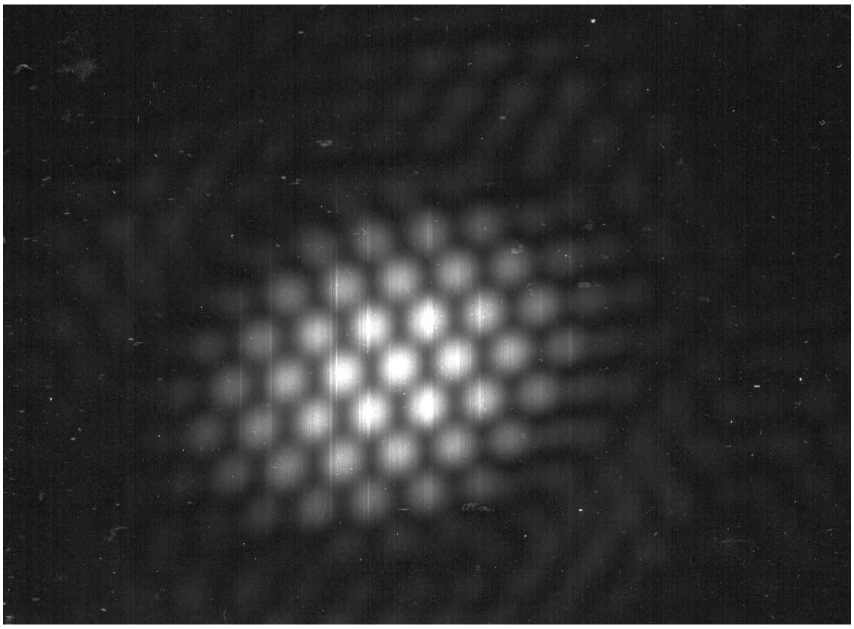


Fig. 16: *Triple-hole experiment*
This is a scan of the pattern behind a triple hole. The three holes form the corners of an equilateral triangle. The interference resembles a honeycomb: it consists of many hexagons. Second order interferences are clearly visible (have a look from a distance). The mathematical peculiarity of this photo consists of the symmetry. We note that a double-hole has three symmetries: two bilateral- and one point-symmetry. In contrast to this, a triple-hole has six symmetries: three bilateral- and three rotation-symmetries. This has an impact on the interference: the patterns need to have the same symmetries as the holes, which in both patterns is the case.

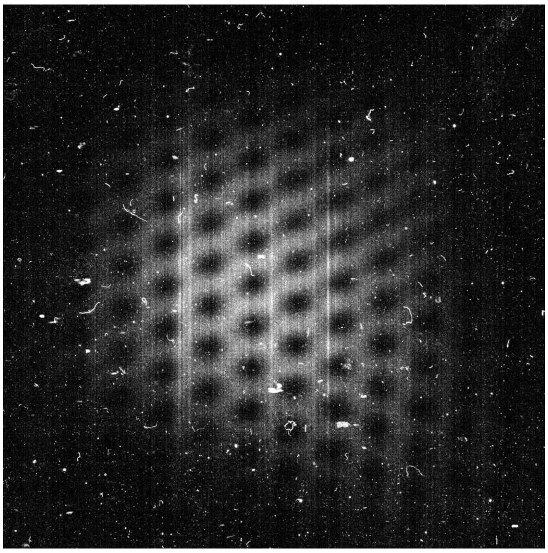


Fig. 17: *Triple hole with pre- and post-selection*
This picture was taken with the same aperture as the picture in ***Fig. 16***. The difference is that a small polarizer was placed on every hole (with a polarization angle shifted by 60°) The symmetries are still present but the picture is a negative of the previous image (the pentagons are black).

3.8 Comment on quantum description

Up to now, only the wave explanation was discussed. Quantum physics explains the polarization phenomena in terms of the gain and the loss of information about the photons. For example, on ***Fig. 13***, it is impossible to check which of the two holes the photon passed. In principle, the photon has a possibility to enter both holes at the same time. On ***Fig. 14***, it would be possible to measure the polarization of a photon so that one is able, at least in principle, to find out which of the two holes the photon went through. On ***Fig. 15***, this information gets lost because the photons are polarized by the third polarizer (post-selection) and the knowledge of the polarization of the photon doesn't provide any possibility to find out the way of the photon through the holes. **A single photon can interfere with itself.**

We note that **only "a potential threat" and not a real measurement is enough to cancel the whole interference pattern.**

4 Low intensity experiments

4.1 *Low-Intensity experiments*

As a first goal I attempted to find single photons on a picture. In the past this kind of experiments by done by exposing photographic emulsions.

Nowadays, the digital photography with its CCD should allow doing the same. CCDs are even more sensitive. The quantum efficiency of photographic paper is smaller than the efficiency of CCDs. Therefore, it should be possible to detect single photons. I wanted to “prove” with relatively cheap material the wave-particle duality of light and the probability waves by measuring the photons that hit only single pixels. In this case the intensity of the image should be caused by a higher photon density i.e. by the larger number of photons impinging on the CCD.

4.2 *Experimental setup*

The light source is a green laser. For the purpose of this chapter this laser has several advantages:

- Green photons have higher energy than red ones.
- The noise of the green pixels is lower than the noise of the red pixels on the CCD.
- The number of green pixels is twice as big as of the red ones.

The laser hits an aperture with a double-hole. The Canon’s CCD of the size 22.2mmx14.8mm was exposed directly to interferences. The objective of the camera has been taken away. The holes are very small (ca. 0.1mm) and are positioned far away. This assures that the envelope can be neglected and the distance between the fringes is much smaller than the size of the CCD. A lot of attention was paid to the shielding. In fact, optimizing of the signal/background ratio was the main difficulty of this experiment.

4.3 *Experimental procedure*

The procedure was:

1. Take the same picture several times with different exposure times and different sensitivities (ISO values). One picture was taken with the laser and immediately corresponding one with the cover on the camera.
2. Data analysis. The values of the brightness of the pixels were presented as a histogram. The signal and the background pictures were subtracted. This gave a mean for optimization of the signal/background ratio.
3. The RAW-data pictures were converted into TIFF.
4. The TIFF files were processed with the Photoshop ® and the new pictures were edit with the “curves” tool. This allows again to suppress some intensity levels and to amplify others in a very precise way.
   The levels which were proofed to have a good signal-to-noise ratio were amplified. Those were especially the levels between 1-10 and 5-15.
5. The picture was saved and further processed with an AstroArt ® program.
6. The x and y-profiles were created.

The main problem of experiments with low intensities is the noise. “Noise” means the pixels that are lit although they weren’t hit by a photon. The noise which influences these pixels is also called dark current. Because of the temperature of the CCD, the electrons of the CCD sometimes get out of their place without being hit by a photon. They get amplified and cause a signal. The noise gets stronger the longer the exposure time and the higher the ISO value is.
I made photos with the highest sensitivity, ISO 1600. However, the dark-current was too high. With less sensitivity, ISO100 the background was suppressed more efficiently.
I optimized also the exposure time. The best results were obtained with 1/10s.

The pictures were analyzed with image processing programs as described above. The result is clearly visible as green stripes consisting of separated dots, mostly in green color. Although not always the single pixels were hit (quite often, the CCD responded in clusters), the distance between the hits was large enough to exclude the probability of double photon hits in the same cluster.

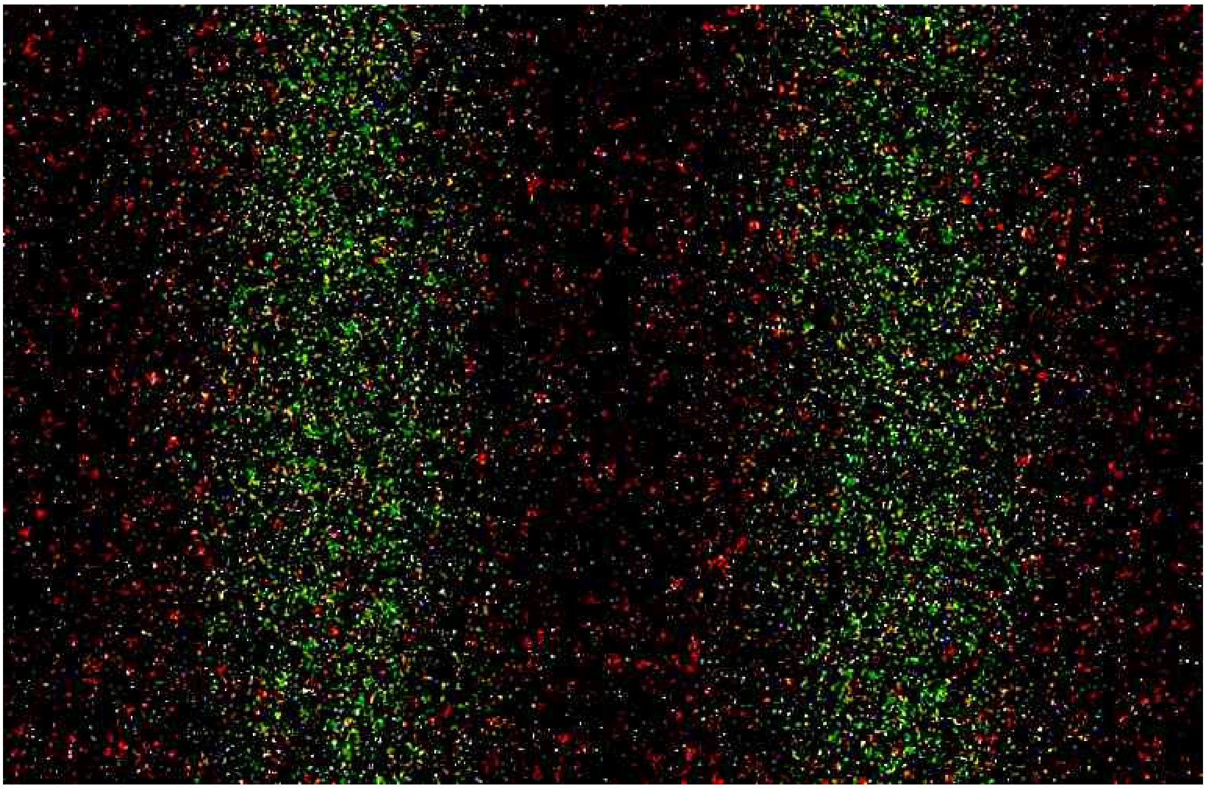


Fig. 18: *Double-slit experiment with low-intensity.*
The picture shows the processed result of a direct exposure of the CCD with interfering laser light. One recognizes clearly single hits arranged into two parallel stripes. the picture consists of many clusters which are produced by single photons. The distance between the strips amounts to 2mm.

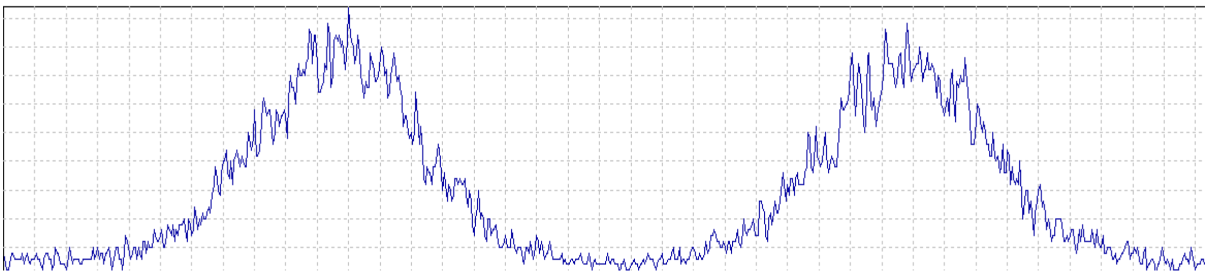


Fig. 19: *Projection of the data from **Fig.** 24 on the horizontal axis.*

The next element of the data analysis was to check how many photons hit the screen. For this purpose I wrote a program in Excel ® which counted all the green hits. The result was around 110’000 in 1/10s, also, 1.1 Mhz.

The laser of power p=5 mW and wavelength λ=532 nm emits:

$F = \frac{p}{\frac{c}{\lambda} \cdot h}$ = 1.34E16 photons per second.

I estimate that the attenuation due to the double-hole is about factor 1000. The attenuation due to the fact that the CCD has covered only a small part of the pattern is about factor 1000. In addition to that the camera can only count those photons which hit on a green sensor and not the whole area of the CCD is sensitive. I estimate a factor 10 for this. In addition, ISO 100 shows only a 1/16 of the amount of photons that ISO 1600 would show, a further factor 16.
Taking into account all the attenuation factors, one expects around 80 Mhz photons on the whole CCD. Although this is about factor of 60 more as measured, the agreement can be considered as acceptable taking into account very crude approximations used in the estimation.

IV Conclusion

I think that both sorts of my experiments were successful. The high-intensity experiments produced beautiful photos which support the theory I wrote about at the beginning of this document. Particularly, the polarization part of this work produced very interesting results.

The low-intensity experiments were successful as well. Esthetically they are not as beautiful as the high-intensity experiments. However, I was very pleased to see in my own experiments the quantum nature of photons.

The next step in this kind of experiments would be time-resolve counting of single photons. With a small group of colleagues from our school, we performed first steps in this direction by setting up photomultipliers used in cosmic ray experiment[7] at our school. This work is in progress.

After finishing my Matura thesis, I'm even more fascinated by quantum physics.

[7] J. Portmann, „Myonen und die Relativität"

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