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Light! What is it really?

Paweł Fiertek
Gdańsk University of Technology/Faculty of Applied Physics and Mathematics/Insitute of Solid State Physics

„My first error was to suppose that the path of the planet is a perfect circle, a supposition that was all the more noxious a thief of time the more it was endowed with the authority of all philosophers, and the more convenient it was for metaphysics in particular.” - 1609r, Johannes Kepler [1].

The story which I am about to tell begins in a small, poorly equipped students' laboratory, which whereabouts seem to be quite symbolic. It is connected to the fact, that it is located under a big auditorium in which for many decades now one may have been hearing physics lectures for the students of Gdańsk University of Technology. As if some unknown planners through the symbolic value of this place wanted to convey that above this lectured knowledge empiricism prevails, which is the final instance of what is and what is not. The beginning of the academic year 2006 began without any interesting occurrences, however this little laboratory started to fill up with students. One of them was a very shy and, it seemed, ordinary girl named Kamila. One day the seminar which she attended was given by the same professor that lectured her. She sat hesitantly in her seat and quickly began to study an instruction left in front of her entitled: „Young's experiment”, nervously peeking around to see if the professor was approaching. She did not have to wait long. After throwing out some unprepared students and questioning the luckier ones who did not have to leave the laboratory, the time came for Kamila. Being the last one to be questioned, the professor made up his mind to do it more accurately. He then sat beside her and began:
- Good morning.
- Good morning, professor.
- What kind of experiment will you deal with at your station?
- From what I have read it will be Young's experiment.
- Read? Let us see what you have read. Could you please tell me about the essence of this experiment?
- It is about light interference. {Kamila answered quickly}
- Alright, could you please elaborate?
- Yes, professor. We have here a diffraction grating through which we transmit a laser beam, next we observe interference pictures on the screen. After this, we have to measure the distance between the net and the screen, as well as the distance between spots of light on the screen, and use those in the formula to gain the diffraction grating constant.
- But Ms! The question I asked was about the essence of the experiment, not the way to convey it and what needs to be measured. That being said, let us start from the beginning. Do you remember what light is from my lecture?
- Yes, but I do not fully grasp this concept. There was something about wave-particle duality at the lecture. I remember that light is an electromagnetic wave in some length range of the wave.
- That is right, now please tell me what kind of experiment did Thomas Young convey almost two hundred years ago in 1801 and why it was such an important experiment?
- Thomas Young transmitted light through a diaphragm in which there were two holes. Next, he observed interference fringes on a screen set in some distance from the diaphragm. That is, he bravely determined them as interferential because at that time Newton's hypothesis, which only assumed particle interpretation of light effects, was dominant. Even though in Newton's times a man named Hook had already postulated the wave nature of light. That is why, it was such an important experiment, because it allowed scientists to question Newton's authority and draw attention to the wave aspect of light effects, which are diffraction and interference.

- Bravo! I see that you paid attention during my lectures. As you mentioned, Young used a diaphragm with two closely made holes in his experiment. What happens to light when it goes through such gaps?
- If light is a wave, then like any other wave, it refracts at the edge. A gap is nothing other than two closely placed edges. That is why the light bends to both edges of the hole, to then propagate as if from a source point. That reminds me of Huygens' law, which states that every point of the wave-front is treated as a source for a new wavelet. If I understand it correctly, the vibration phase of the wave coming out of the gap should be the same as of the incoming one?
- That is correct. {The professor stated with satisfaction, knowing that at least one person in the laboratory knew something more than just facts from the instructions he landed out. Being very pleased with the answer to his question, he continued the dialogue}
- As you mentioned before, the light interferes with itself creating a pattern, which we then call an interference pattern. Could you please elaborate on this topic?
- About interference? As I remember from the lectures, interference is a phenomenon in which different waves of the same type overlap at one point, this also occurs with electromagnetic waves.
That’s why, at least two different waves should be transmitted to the screen to make an interference pattern, and why there was a diaphragm with two holes used in the original experiment. However, what we have is a diffraction grating. Are there two holes in it?
- Ms Kamila! I do not think you know what a diffraction grating is? At the very beginning of our conversation, you mentioned that you would be calculating the diffraction grating constant. But it seems that you have no idea what a diffraction grating is, and even further you do not know what its constant is?
- The instruction didn’t mention that. What is it? {She asked quietly under her breath}
- Ms Kamila, a diffraction grating is nothing more than, for example, a plain piece of glass with many small slots cut out very closely to each other, which acts as a diaphragm. It can also be a...
- Yes! I know now! {Kamila shouted with enthusiasm, not acknowledging the hint of embarrassment on the face of the professor, who was not used to being interrupted} The unfilled area are the gaps in our diaphragm and the distance between them is the diffraction grating constant. But then, why did Young use two diaphragms in his experiment?
- You see, the best way to explain this is on a drawing (Fig.1).

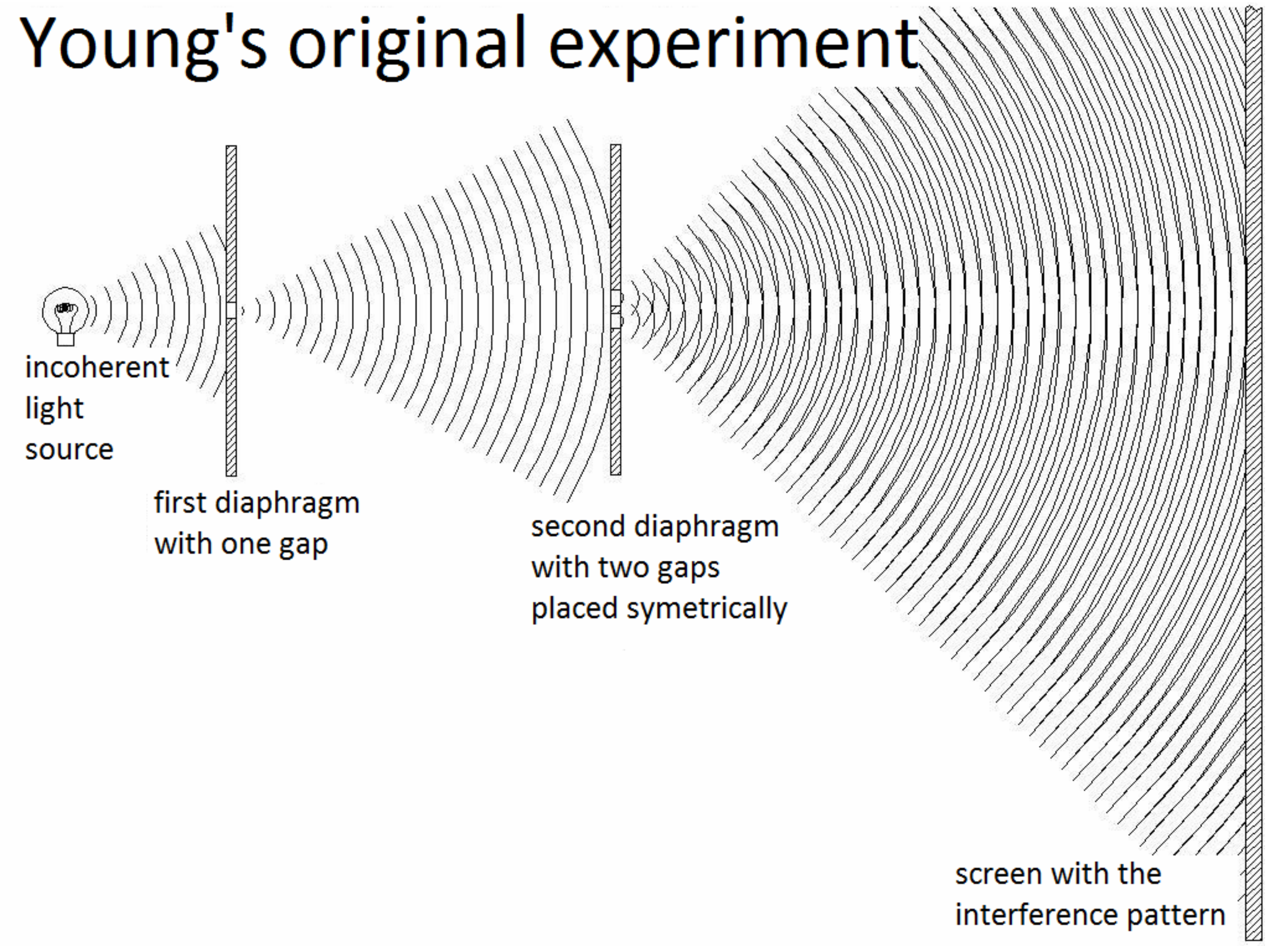


Fig. 1 A diagram of Young's original experiment.

- As you remember Young conducted his experiment over two hundred years ago, in an age where the views on light were dominated by Newton's considerations on the topic, in which he clearly objected to light being a wave. That is why, Young's proof of the wave nature of light had to be efficiently convincing so that he was not laughed at and suspected of heresy. Having that in mind, he paid more attention to the details which enabled his further considerations in a way that his listeners would have nothing to object to. Based on the drawing, can you see what detail I have in mind?
- I think so. As I mentioned before, the phase of the wave coming out of the gap must be the same as the one transmitted to the diaphragm. From what I see on the drawing, the wave-front transmitted through the two gaps on the second diaphragm has the same phase. That means, that the phases of the waves coming out of the gaps must be the same. But is that really important?
- Yes, that is very important because what happens on the screen depends on the phase differences between two light beams that are transmitted to the screen. Young explained the creation of fringes on the screen through the difference in the light's paths when coming out from the first and the second gap. If the screen and diaphragm are motionless, then we must assume that at every moment in time the path which light takes from the diaphragm to the point on the screen does not alter. If the pattern is to remain motionless, the difference between light wave phases coming out of particular gaps may not change in time. To accomplish this, Young had to use another diaphragm, which he needed only to make sure that the light transmitted to both gaps had the same phase (with the assumption that we do not have accidental shifts of the phase in time. That is when waves arriving at the screen were transmitted in different moments in time.). Without that additional gap, his listeners would rightly accuse him of falsehood on the assumption that daylight as a wave is fully incoherent. In the modern version of his experiment, the first diaphragm is not used. Do you

remember how this problem is dealt with at present?
- The instruction mentions that interference patterns may not be created with incoherent light, that is why the use of laser light is needed to conduct this experiment, which is coherent. I think that is how this inconvenience was solved. (Fig.2).

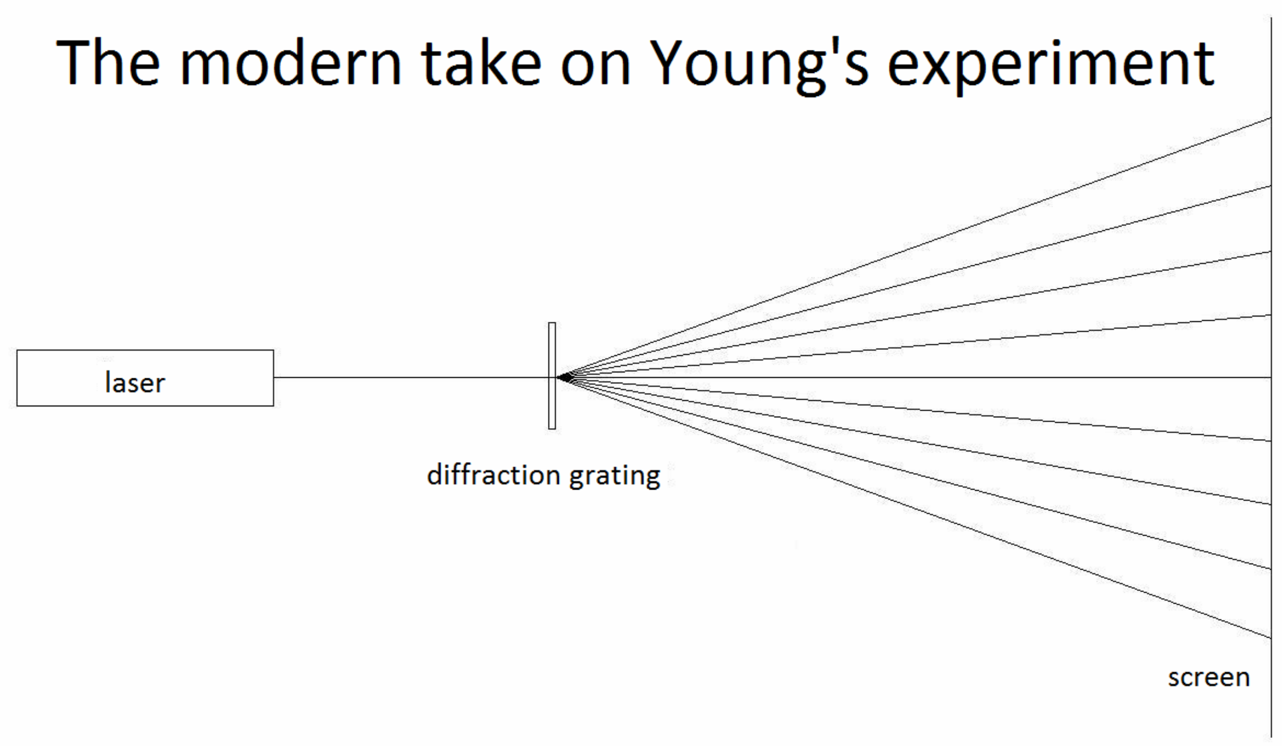


Fig. 2 Modern take on Young's experiment diagram.

- That is right. Could you please tell me what coherent light is?
- In the light of those mentioned facts, it is a very simple question professor. It must be such a feature of light that when we take a random intersection of a light beam perpendicular to its propagation, then at every point of the intersection the phase of the light wave must be the same.
Then such light falling on the diaphragm with multiple apertures will result in a number of outcoming wave sources from each separate aperture, but with the same phase or constant phase shift (e.g. rotation of the lattice against the direction of laser light).
- You are really clever indeed! That's exactly it. Two hundred years ago people knew nothing about the sources of coherent light and therefore Young's audience could easily claim that the light he used for his experiments was deprived of the said feature. You could even go further. Thermal light produced by well-heated objects such as a light bulb or a glowing piece of metal is characterized not only by a non-uniform phase of the light beam intersection, but also the phase of a given wave changes randomly at different points in time. Therefore, one can say that such source of light is completely incoherent both in time and space.
It results from the fact that every atom of a heated object emits a quantum of light independently and in a random direction.
- So, it's my understanding that in the case of incoherent light from each aperture of the diffraction grating there is a light wave released at a random phase in relation to others and, what is more, randomly variable in time?
If the light from a number of apertures with random phase shift fell on the screen, almost all of the waves would add up in such a way that a vast majority of them would cancel themselves out resulting in a dark image, i.e. no image at all.

- That's exactly it. Therefore, no image can be created in Young's experiment with the use of incoherent light. Right, Ms. Kamila, we are running out of time, and we still need to conduct the following experiment. Here we have got a laser pointer which will serve as the source of coherent light with the wavelength of 632.8nm, diffraction grating, a set of thin wires, adaptable single diaphragm and a screen safety grating consisting of many thin wires crossing at right angles.

First of all, you will have to calculate the lattice constant, then come up with wire thickness and the distance between edges of a single aperture. With regards to the wire and the aperture provided formulas are similar. Later, if there is still time left, you can also familiarize yourself with the screen safety grating, which makes it possible to obtain typical clearly visible interference patterns in the form of the network of points.

- Yes, professor.

Once the conversation came to an end, Kamila proceeded swiftly to set up the laboratory equipment, and soon after, she could carry out initial measurements. Having transmitted the laser light through the diffraction grating, she measured the distance between the grating from the screen, as well as the distance between the first and the second light spot from the centre of the image. Having taken into consideration all measured quantities, she presented the lattice constant as: 4,87±0,02µm and proceeded with other measurements. Little did she know what awaited her during the experiment with a single aperture. To her surprise, she realized that the single aperture produces the same fringes as the diffraction grating, however with much smaller displacement from the centre of the image and a larger number of spots. From her recent conversation with the professor, she remembered that in order to create an image on the screen in Young's experiment, at least two sources of light were needed in order to achieve interference.

- It's in contradiction with theory! {She shouted unintentionally. Having heard that, the professor approached her}

- Stop screaming, please! What happened Ms Kamila?

- Professor. At first, we concluded that in Young's experiment there must be present at least two sources of light with the same phase in order to achieve the stable interference image on the screen. Here, we have got only one aperture, and with that being said only one source of light, and we still see interference fringes. Surely, there must be something wrong with Young's conclusions?

{She said confidently, proudly raising her head}

- Not necessarily. The answer to the question regarding interference fringes produced after the transmission of light through the single aperture requires more complex explanation. Do you remember Huygens' principle?

- Yes, every point on a wave-front may be considered a source of new wavelets.

- So, the front of a light wave falling on a single aperture may be divided into many wavelets of new point waves, which are present between the aperture edges. Then, the light from those sources continues to interfere on the screen. If we are going to gradually reduce the distance between those sources of light until it reaches zero, and their number to infinity, then after summation (i.e. integration) in the scope between the first and the second edge for those waves, we will receive a fringe image on the screen. So, the wave theory does not point to any contradictions in that regard.

- I guess that the light must still be coherent?

- I think that we can safely assume that.

- You see, professor. Please, forgive me but this interpretation seems to be far-fetched.

- Why is that?

- Because I'm trying to figure out why Young used only two apertures and also why did he refer only to the distance between those apertures in his analysis? If the image appears on the screen also in the case of a single aperture, then such fact must be taken into consideration in the analysis of two apertures. However, he didn't do that. Moreover, based on the formula introduced by Young, the image, having been transmitted through the apertures, depends only on the distance between the apertures, and not their size. Because the size of apertures and the distance between them do not have to be the same, and as a rule aren't, then perhaps we should expect two separate overlapping

images, which I haven't noticed. Moreover, please notice that the design of Young's experiment is faulty (Fig.1) because it works on the assumption that, having been transmitted through the first diaphragm, the light will react like the wave and will illuminate the second diaphragm uniformly. However, the second diaphragm will not be uniformly illuminated within the scope of the apertures, because it is just there that the fringes from the first aperture should appear!
- Yes, you're right. For now, please assume that there are no faults whatsoever, and later I will try dispel your doubts.
The professor, puzzled with a troublesome question, left hurriedly towards the other group of students, who at that very moment were in need of assistance, leaving Kamila alone with new doubts forming in her head. The student, not knowing what to do, started to play with the monitor safety grating putting it in and out of the laser light beam and at the same time watching the interference images appearing and disappearing from the screen. At one point, she realized that a similar problem, however on a much larger scale because it was more visible, occurs in this instance. She summoned the professor again.
- Professor, can I speak with you? I have some doubts that I am not sure how to deal with.
- Yes, what seems to be the problem? {The professor approached the student in a composed manner, hoping that this time the problem was much easier to solve}
- Professor, I started to play with that big monitor grating. I reckon, that it is made of parallel thin metal wires stretched over a frame.
- Yes, in two perpendicular directions, and therefore you should be able to see a more complex image than the one produced with the use of diffraction grating or a single aperture (Fig.3).

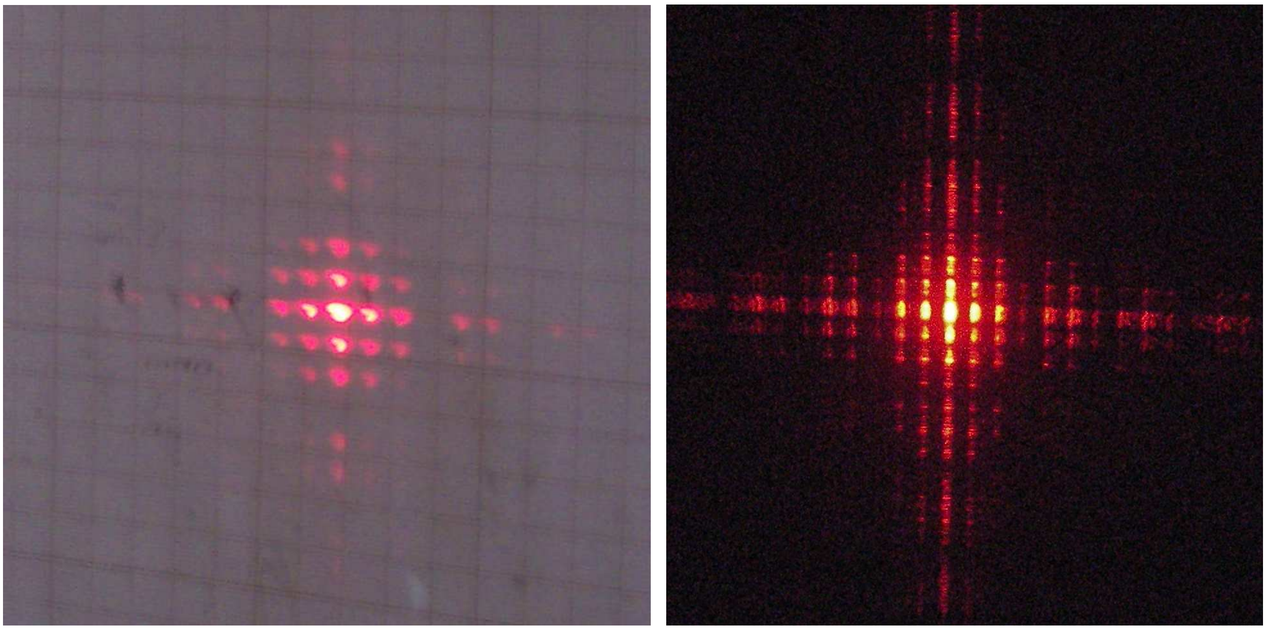


Fig.3 The image of fringes produced by transmitting a laser beam through the screen grating.

- That's right, the fringe image arranged itself not in one but in two directions. Anyway, I was wondering what calculations can be made based on the image? In the case of the experiment with diffraction grating, I had to calculate the distance between apertures. In this case, it would be the distance between the wires of the grating. In the experiment with single wires, we could observe the creation of interference fringes, which, according to the script, depends on the wire thickness. Whereas the experiment with the single aperture was meant to allow me to calculate the distance between the edges, which, in this case, would be interpreted as the distance between the edges of the wires in this grating. So, I was wondering professor, what can be calculated based on this image? Each of the presented quantities is of different physical dimension and should produce

different images on the screen, whereas what we are seeing is just a single image.
- You know what? {He continued with a trembling voice after a short pause} – I don't know. What you are saying is really interesting. Please let me think about it for a while. Could you tell me what the diffraction grating constant is?
- Of course, professor. It's 4,87±0,02μm.
- You have clearly forgotten about two significant digits! { The professor has slightly reproached Kamila for the incorrect final notation} You see, it's almost time to submit your report. Have you come up with all your conclusions yet?
- Not yet, professor, however everything is in my notes.
Having browsed through the student's notes and after confirming the validity of other calculations, the professor gave the final grade for the report and greatly relieved ran from further questions that he did not know answers to at the time. He found his escape because after a moment a different group of students approached him with the intention of submitting their report. At the end of the day, he came back to the laboratory and repeated all of the experiments related to diffraction and interference, however finding now explanation to the questions posed by Kamila. Beginning to doubt the validity of the theory taught by him and others, he decided to at least find out if the formula introduced by Young, and applied in the calculation of the diffraction grating constant, is correct. To that end, he took the grating to the laboratory where he was able to take photos of it at different magnifications under a photon microscope, which he then compared with the photos of the standard version taken with the same equipment (Fig.4, Fig.5).

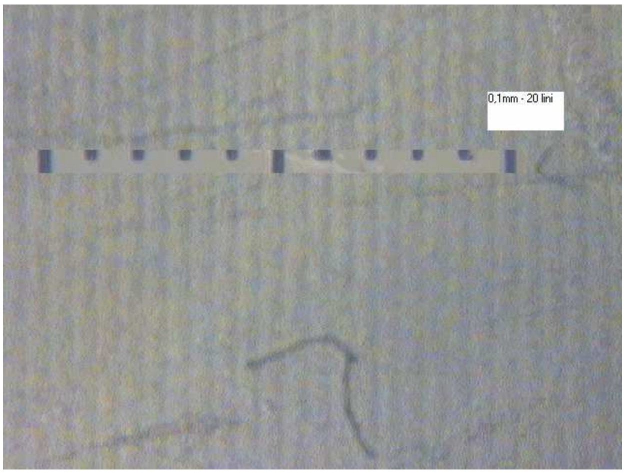


Fig. 4 The photo of the diffraction grating under the photon microscope with a marked standard version scale.

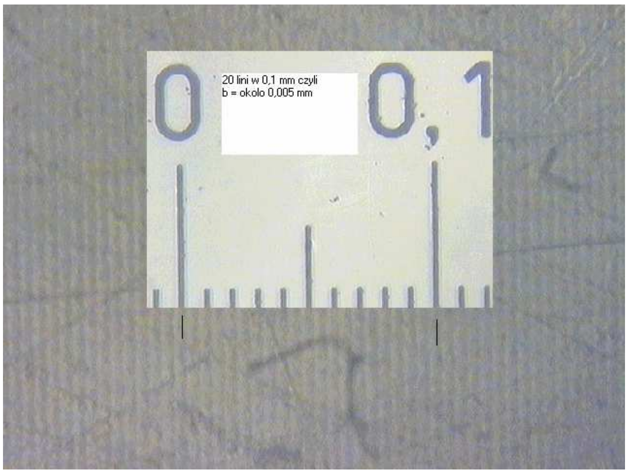
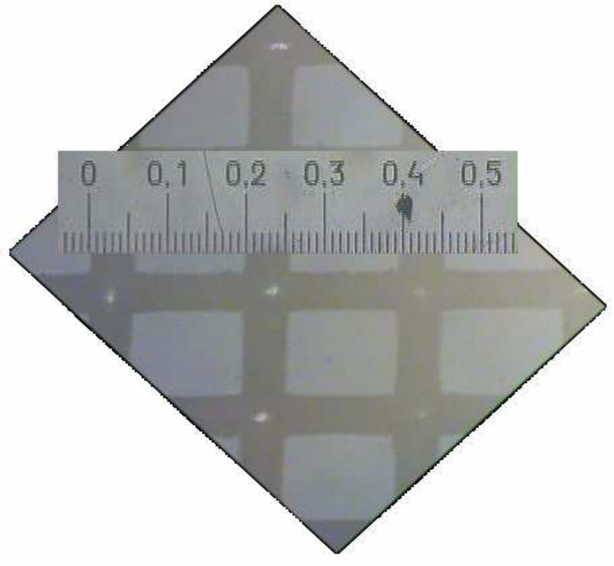


Fig. 5 The photo of the diffraction grating under the photon microscope with a marked standard version scale.

Based on the photographs, the professor determined that every 0.1 mm of the standard version is matched with 20 lines of the diffraction grating on both photographs. He concluded that the distance between the apertures for the laboratory diffraction grating equals approx. 5μm. Bearing in mind that the result of the student's experiment was below this quantity, he came back to the laboratory and took his own measurements once again. The result he got was slightly lowered, however close enough to the measurements taken with the use of the microscope. This slight discrepancy between the results might have been blamed on a relatively low accuracy of the measuring equipment in the student laboratory. As a result, he assumed the obtained result is consistent with the distance between cracks in the diffraction grating.

Then, the professor took a closer look at the monitor grating. After all, he did not know the answer to Kamila's question. What physical quantity may be determined based on Young's deliberations with regard to the screen grating? He took the photo of the grating and the standard version as before, but with the use of a different object lens (Fig. 6). The photograph revealed that the grating consists of fibers ~50µm in diameter in both directions. Whereas the distance between the fibers in the photograph would change depending on the measured direction. In the first instance it equaled ~200µm, while in the second ~170µm. So, the distance between the fiber edges was also different and depended on the direction of the measurement: ~140µm and ~120µm respectively.



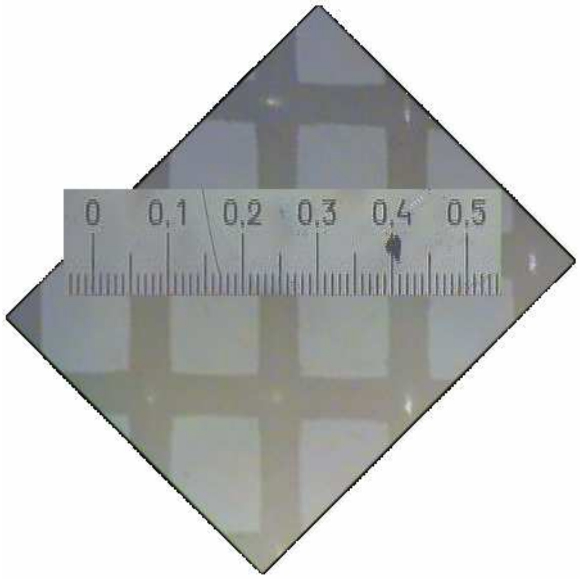


Fig. 6 The photograph of the grating in two different positions. The standard version scale is in [mm].

Having determined the dimension of the grating using the microscope, it was now time for measuring the positions of interference fringes. The professor measured the distance between the diffraction grating and the screen. He also took the measurements of the location of five closest fringes (rows from k=1 to k=5). He then calculated the distances between the apertures using the formula based on the premises of Young's wave interpretation, while also estimating the uncertainty of obtained results (Tab.1). The length of the laser light wave was determined based on the measurements of the position of interference fringes for the diffraction grating with a known distance between the apertures (600 lines per 1mm).

Tab. 1 Fringe calculations for the screen grating for two perpendicular directions.

λ =	639,6 ± 1,1nm				L =	1575 ± 2mm		Sx = 2mm	
Horizontal position				relative	Vertical position				relative
k	x	d	Sd	error	k	x	d	Sd	error
	[mm]	[mm]	[mm]	[%]		[mm]	[mm]	[mm]	[%]
1	13	**0,155**	0,024	15,5	1	11,5	**0,175**	0,034	19,4
2	25	**0,1612**	0,0067	4,2	2	22,5	**0,1791**	0,0092	5,1
3	37	**0,1634**	0,0033	2,0	3	33	**0,1832**	0,0045	2,5
4	50	**0,1612**	0,0023	1,4	4	45	**0,1791**	0,0028	1,6
5	62	**0,1625**	0,0023	1,4	5	55,5	**0,1815**	0,0025	1,4

The obtained results, despite slight disparities (the results were lowered compared to those obtained on the basis of the photograph), are the most accurate with regard to the distances between the wires in the grating.
The distance in question equals the distance between the apertures (holes in the grating). The professor was very satisfied with the result, because it was close to what might have been expected based on the premises of the wave interpretation. However, the interference image on the screen

also portrays variations in the amplitude of certain fringes, which reveals the existence of additional somewhat ‘bigger’ fringes (Fig. 3).
The location of the centre of those ‘fringes’ is a little harder to determine, because it pertains to the maximum location of the amplitude related to the changes in intensity of regular fringes, and not the location of the interference fringe per se. Therefore, the professor assumed that the accuracy of location of such quantity should equal $S_x = \pm 5$mm and determined this quantity as: ~55mm and ~100mm in both directions (vertically and horizontally), for the first and second row (k=1 and k=2) respectively. Based on such parameters derived from Young’s wave deliberations the following distances between ‘the apertures’ are presented: d_1 = 0,03664 ± 0,00088mm d_2 = 0,04032 ± 0,00084mm respectively, for k=1 and k=2 respectively. As a result, the calculated quantity obtained in this way is most relevant the thickness of the wire, which is the same for both directions. At that point, the professor was struck by two matters: first of all, ‘big fringes’ are not fringes at all but determine the maximum location of the variable in amplitude of the regular fringes. Under those circumstances, the deliberations based on Young’s interpretation do not necessarily have to provide an explanation for those additional effects in the interference picture. Secondly, the obtained result of ~40μm, and even more so ~37μm significantly differs from the wire diameter, which equals ~50 μm (based on the measurements taken with the microscope).

Not being entirely sure of the validity of application of Young’s wave deliberations for the purposes of drawing conclusions regarding the location of ‘big fringes’, the professor assumed that the disparity does not pose a problem, because the location of ‘big fringes’ requires a different explanation and does not have to depend on the diameter of the wires in the grating. Whereas other results, even though differing slightly from the photographs obtained with the use of the microscope, overlap with Young’s theoretical deliberations. In this case, the location of the fringes is contingent upon the distance between the apertures in the grating. Both the screen and the diffraction one. Then, having rightly concluded that the slight disparities in the measurement of distances between the apertures might result from a pretty low accuracy of the laboratory equipment, he went home for a moment of deserved respite not thinking twice about the matter.

A week passed during which Kamila, while swamped with her other commitments, had no time for careful deliberations regarding the matters which had been on her mind since the previous class. This time her exercise was very easy and dull, taking only a short while to complete. Being about to leave the room, she took one more look at Young’s experiment and noticed that there was no-one there. I guess they weren’t prepared, she thought to herself. She sat beside the stand and, having switched on the laser, she started to play with the screen grating. As before, the image kept appearing and disappearing whenever she would expose and then remove the grating from the laser light beam. At some point, while she was focusing on a single fleck of laser light diffused across the wall, she waved the grating before her eyes and saw the image that was very surprising to her. It was something, not discussed in the manual, and also something that the professor did not mention during last week’s classes. Watching a fleck of light on the screen through the grating, one could see the same image as in the regular experiment (Fig. 7).

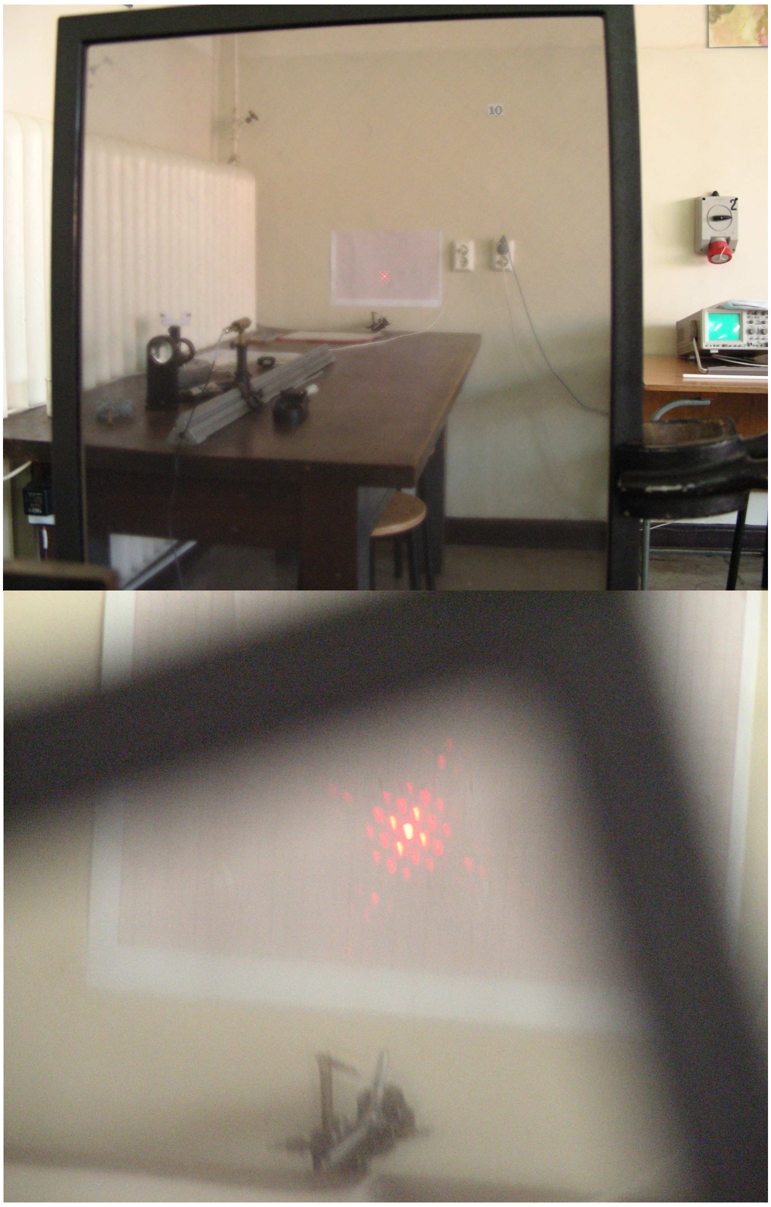


Fig. 7 The image of a laboratory table with an optical rail and a mounted laser seen through the computer safety grating. On the right hand, the blow-up of the photograph.

This instance made Kamila decide to get more insight into the matter as she began to take a closer look at the produced images not only in relation to the screen grating, but also the diffraction grating. She realized soon enough that the diffraction grating gives the same effect. Due to the fact that the human eye is not the same as a big screen or a wall on which she previously observed the same images, she was wondering if she was dealing with the same phenomenon. Is the similarity of observed images only a matter of random selection? As she continued to play with the gratings she realized that the integrity of light in not required for the creation of the so-called “interference picture.” In the original experiment the light falling on the wall was emitted directly from the laser, and only then onto the screen. It was then easy to prove the existence of the requirement related to the integrity of light. Kamila’s train of thought revealed itself as followed: Whereas the light falling on the wall is coherent (since it leaves the laser directly), while being diffused across an uneven wall with the unevenness far in excess of the length of the light wave it cannot retain its coherence. Since the images observed through the grating were exactly the same as those in the original experiment, Kamila assumed it was the proof that the light coherence is not required for the occurrence of observed phenomena.

That day Kamila could not fall asleep. Too many questions and thoughts were stuck in her head. She decided to approach the professor the following day and tell him about her discovery. After all, it was not without reason that Young used the first diaphragm with a single aperture {Which does not provide the light diffusion (diffraction) in accordance with his assumptions, because a single aperture also produces fringes on the screen!). Also, it is unequivocally stated in books that the source of coherent light (e.g. laser) must be used so as to obtain the 'interference image.' Besides, the professor explicitly explained to her during classes why this premise was so important. Meanwhile, she is observing images which, in her opinion, are produced with the use of incoherent light.

The professor listened to Kamila with considerable interest, however he did not find her theory credible. Finally, he asked her to accompany him to the laboratory, where it was possible for them to take a closer look at the matter in question. Once they got there, Kamila hurriedly switched on the laser and a shining red spot appeared on the wall.

- Professor, please take a look. If we cut the laser beam with the screen grating, then we will receive the interference image (Fig.3) Based on what you explained to me last time, we can assume the a coherent beam of laser light falls on the grating, where it is subject to diffraction in the apertures and subsequently interference takes place on the screen. So, if we move past all of the previous reservations regarding the case of a single image, then everything seems to be in place regarding Young's wave interpretation. The main premise of light cohesion is met by the use of laser light in the experiment.

After moving the grating away from the laser beam, a single point from the diffused light reappeared on the screen. Kamila continued the conversation.

- We should first ask the following question: what can be said about the light falling on the wall?
- It's monochromatic (one colour – a certain wave length or frequency) and coherent.
- And what can be said about the light that reaches our eye?
- It's still monochromatic, but is it coherent? Certainly not.
- Exactly, so please take a look at the shining fleck of light through the screen grating.

The professor held the grating before his face. At that moment he saw the same image as the one characteristic of the original experiment (Fig.7). The image was less intense, but that however was of no surprise because it was possible that less light could reach his eyes due to the longer distance. It was rather the following question which was vital: why at all is he able to see 'the interference image' if the light, which passed through the grating, was not coherent? Is it possible that the observed phenomenon does not require the light coherence? Of course, he could not admit that. He knew well enough what consequences it would have regarding the commonly accepted theory of light.

- Maybe the light diffused across the wall is partially coherent? { He suggested and thought that what he had just seen could still be explained with the wave interpretation}
- I didn't realize that the light diffused across the wall might retain part of its original coherence. Then of course, the problem wouldn't exist. And if, instead of the laser spot, we could watch other sources of light through the grating. I mean those which are certainly incoherent. {Suggested Kamila}
- Actually, that's not a bad idea. I think that we could use a regular light-bulb. Thermal light emitted by the light-bulb would certainly be incoherent. In this instance, certain atoms of a heated fibre separately emit light quanta in different directions and at different moments in time. I have mentioned that before.
- I know! {Exclaimed Kamila} Yesterday during classes I was doing the experiment regarding the examination of a photoresistor and photodiode. In this exercise one uses a light-bulb as the source of white light which is then transmitted through the rotating prism. This way, we changed the wave length which was falling on the examined photoresistors, etc. Because in this experiment we used a high-intensity light-bulb, then after being transmitted almost monochromatically through the prism the light should retain its intensity.

- Let’s do it and see what transpires!
They have prepared the stand as presented in the picture (Fig. 8).

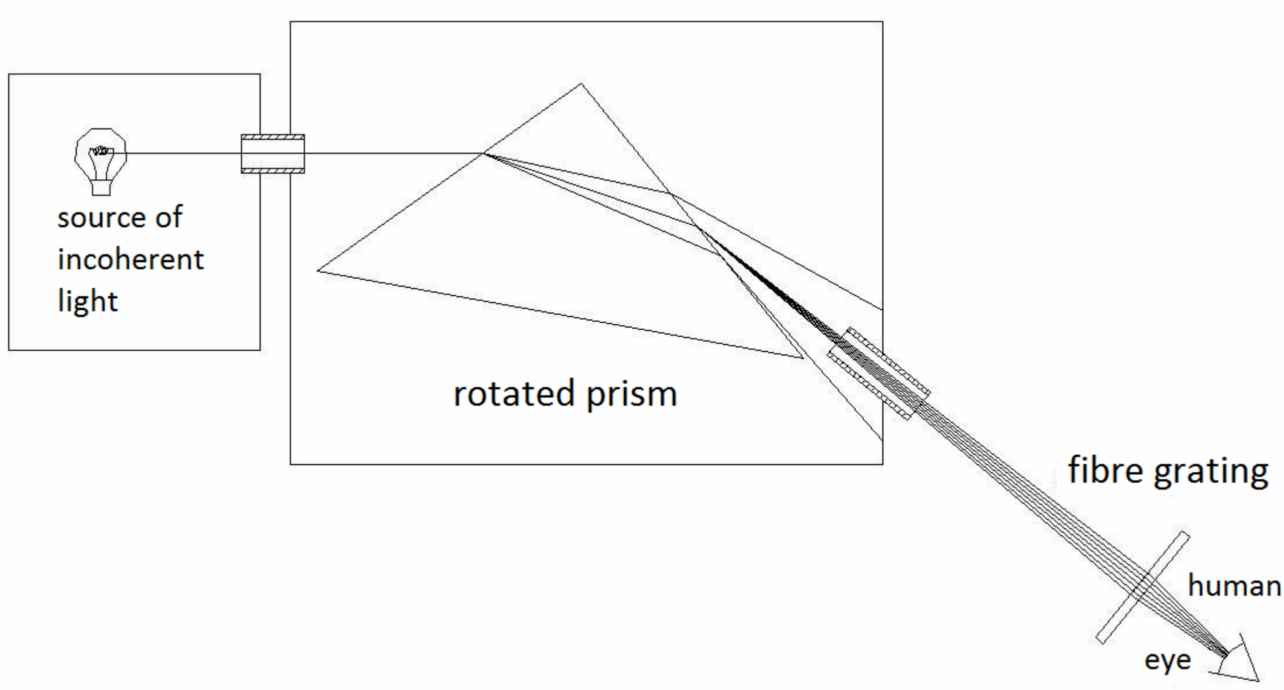


Fig. 8 The experiment diagram showing the creation of fringe-patterned images for the entirely incoherent light (light-bulb).

Because the stand preparation required only the connection of the light-bulb power supply and the removal of the photoresistor, it took them only a moment. Kamila swiftly set up the red colour of light so as to make it look as the spot produced by the diffused light visible in the previous experiment.

The professor lifted the grating and held it before his face. He did not try to hide his surprise when he realised that he could see the same image as before but in a much clearer way – all due to the fact that the light that reached his eye was much more intense. Now, it was clear that even if previous assumptions regarding partial cohesion were correct, they were irrelevant because the observed image was the result of the incoherent light (light-bulb). It could only mean one thing. The need for light cohesion in this instance did not apply! Kamila, seeing the surprise on the professor’s face, quickly realised that he was seeing something interesting. She approached him swiftly and asked for the grating so as to take a look herself. They both realised the volume of the discovery, however did not know what to think of it. In the meantime, Kamila rushed to the prism and started to rotate it asking the professor to take one more look through the grating. This time, the colours changed, however the image remained the same. The only aspect that would change slightly was its size, which was related to the fact that the light of different colours is diffused across the grating at different angles.

- What would happen if we looked at the grating directly through the light-bulb? {Asked Kamila}
- Let’s see (Fig. 9). {Responded the professor}.

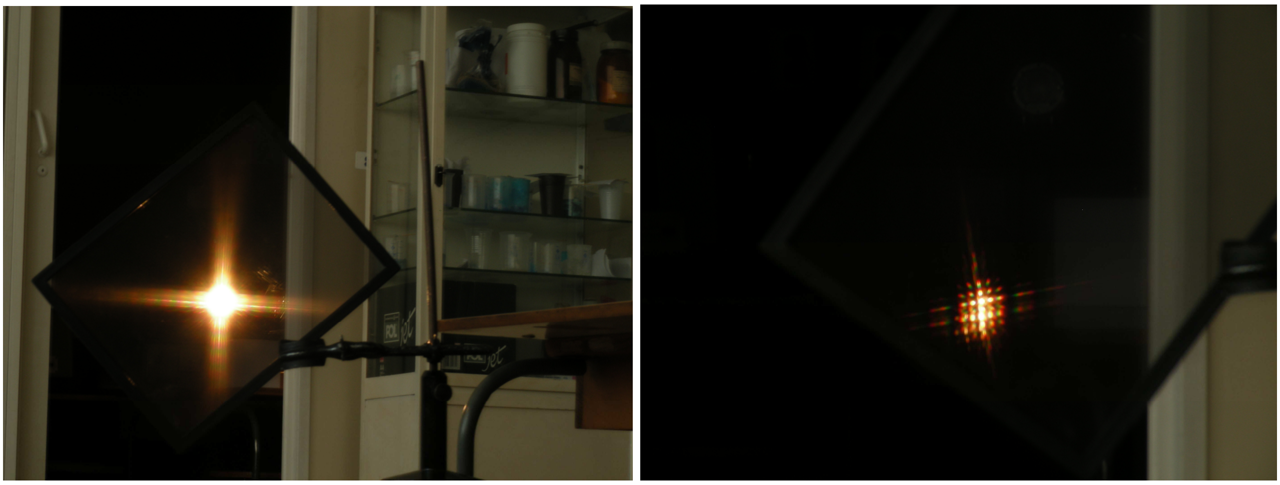


Fig. 9 The light-bulb image seen through the grating.

- These images are so beautiful! {Kamila exclaimed with excitement} Now all the colors create a cohesive and extremely vivid image {Which gives an amazing visual effect for highly intensive light} However, even with the use of a small bulb it is possible to notice highly visible colorful fringes.
- There is no doubt about that. {The professor stated in a hushed voice}The phenomenon described by Young does not require coherent light and this fact is of tremendous significance for the explanation of this occurrence.
- Wouldn't it be possible to explain this occurrence without the stipulations of the coherent light theory?
- I am afraid that it won't be possible to do that with the use of the wave interpretation. The interpretation of this occurrence nowadays is in fact purely geometrical and is based on the calculation of the differences in distance covered by certain beams of light. If the observed images remain stable, and the arrangement is not subject to any changes, then we must assume that the differences in distance are also not subject to change in time. Then, the initial conditions for light must also be accurately defined. It means that we must assume that the light is coherent. If it wasn't the case and the phases of light beams leaving certain apertures would change randomly, then also on the screen we would be able to see a random phase shift, regardless of the actual differences in distance. Then, it will be no longer possible to explain the existence of minimum and maximum light intensity on the screen based on interference. The discovery of the fact that in Young's experiment light coherence is not required does not of course mean that this occurrence is not in existence. It, however, shows that we must bid farewell to the wave interpretation based on interference. Or at least the interpretation which is based on calculating the distances between the 'sources of light,' and the point on the screen (light observation point). I'm afraid that the explanation of this phenomenon is not possible with the use of present methods, without referring to the main premises of light coherence. However, to be certain, I'll consult a few books to see what exactly has been written on that subject.
- Right now, I understand that I might ask any professor, e.g. during the lecture, to explain this phenomenon and they would eventually have to refer to the premise of light coherence so as to make use of the wave interpretation. Then, I would just have to make sure that they won't be able to apply the premise in question. As a result, they won't be able to come up with the explanation for the phenomenon. They would have to try to explain it in a completely different way.
- If one has to assume that the initial phase in a single aperture or multiple apertures (or phase distribution, when the phase is transformed into a certain quantity while being transmitted from one aperture to the other) is well defined, then of course there might be a problem with explaining this occurrence on the basis of the wave theory. It would be, in fact, in contradiction with the premise of

light coherence, because the experiment would prove that the light doesn't need to be coherent at all. So, we mustn't assume that we know the distribution of the light wave phases at the entrance to the apertures. What's more, we are obliged to assume in that case that the initial phase is random in space and that it may be subject to random alterations in time. However, we must keep in mind that light may be coherent to a certain extent. E.g. it may be assumed that for the beam of incoherent light leaving the incoherent source a certain small extract of such beam could be regarded as coherent. Then, even if we assume that the source of light is not entirely coherent ,we will be at least able to venture a theory revealing that for certain apertures light may be coherent and based on that we could still try to apply Young's deliberations.

- With all due respect professor, I am afraid I don't agree with you. {After a while Kamila decided to continue}

- First of all, the source of light of thermal origin is emitted in the form of single photons, with no cohesion between them. So, the cohesion of a light beam leaving such source would be applied only to one photon.

Having said that, please tell me what is the cross section of a single photon and is it really subject to change depending on the distance from the light source? I find it really hard to believe that because it would be completely ludicrous and in total contradiction with the experiments, where single photons are received regardless of the distance between the light source and the detector as well as the latter's size. Individual photons are not in the same phase and should in part cancel themselves out. That would be true if their cross sections overlapped and were of significant size. In the case of multiple photons overlapping, we shouldn't be able to see anything for incoherent sources of light, which is in contradiction with the experiment, because the light coming from the incoherent source is visible even when it is very intensive. Which is when a significant number of incoherent protons should overlap. Secondly, the size of apertures of the screen grating is quite considerable in relation to the wavelength (The wavelength is not the same as the photon cross quantity!). To follow up on that, we would certainly have to assume that a different phase for certain apertures would occur when it comes to the screen grating. In fact, the size of apertures is so significant that between the edges of the aperture a considerable number of photons would certainly fit in. Therefore, even for a single aperture, it must be assumed that between its edges there are many wave sources characterized by a random phase. It is random in the same way as the phase of emitted photons on individual atoms of the incoherent light source. As a result professor, I can't agree with you that it is still possible to assume in this case that the light is coherent. If the source of light is incoherent in its entirety, then it is incoherent with regard to all of the aspects. Otherwise, we could endlessly argue trying to define the cross section of a single photon. Even if we assume that the size of the aperture is so small that only one photon can pass through it, then, such photon, upon reaching the screen and running into another photon from a different aperture, will be characterised by a random shift of phase in relation to its counterpart. By adding the waves of such photons one would get a result of a random quantity regardless of the location of the fall of the photons on the screen. What is more, such photons would have to be emitted at different times. That would be the case especially with regard to the fringes located further from the centre of the image and more distant apertures.

- Indeed, it could be subject to a long discussion if we attempted to establish for which part of the incoherent beam cross section we would get a coherent beam. Recently, I have checked under the microscope the size of the grating used in this experiment. I have got the following results: the distance between edges was 120µm and 140µm depending on the measurement's direction. The distance between apertures was 170µm and 200µm. If we assume that the size of the cross section of a single photon is directly related to the length of its wave, then the light used in this experiment would pass between the edges of 130µm/640nm(Tab.1) ≈ the width of 200 photons. So, the figure is high enough so as to rule out any suggestions that within the area of one aperture we could have only one phase! Even more so, we mustn't assume that the phase remains the same for separate apertures. We really seem to have a problem because we can't refer to the premises of light coherence!

- Professor, I must say that assuming that the cross section of the photon is equal to the wavelength is rather naive. We have already concluded that the light emitted in the light-bulb is considered a thermal source, whereby each separate atom emits light in a random direction and phase. That is to suggest that the cross section of the photon should be rather reflecting the size of the atom. It is a very sensible assumption if we take into consideration the absorption of photons by individual atoms, or complex particles, e.g. colouring agents.

- Indeed, I must admit that it didn’t cross my mind. The absorption of photons by coloring agents or other absorption centers suggests that the photon would have to be more spatially located than what is suggested by such parameter as the wave length. In this case, we would have to assume that the cross quantity of the photon would at most assume the size of a single large particle of a coloring agent. If not smaller, in fact.

It means that, even more so, we mustn’t assume that it is possible to get a coherent beam of light following its transmission through a single aperture, let alone many of them. This is because the number of non- overlapping incoherent photons fitted between the edges of the aperture would be even greater than I previously anticipated. To be honest, I can’t really imagine the existence of a mechanism whereby the photon would be fully absorbed by the atom or a chemical compound and where the cross section of the absorbed photon would be much larger than the size of the particle absorbing it. Of course, that is a problem if we assume a purely mechanical approach to the discussed matters and stick to the premises of the wave interpretation with regards to the nature of light. Quantum mechanics allows that, however without providing any sensible mechanism. Of course, I mean the mechanism from a classical standpoint, i.e. one that can be fully conceived.

{After a moment of silence, Kamila, looking nervously at her watch, decided to end the conversation}

- Can I work in the laboratory after the classes? This issue is like a really compelling mystery, maybe I would manage to find some other inaccuracies. I would appreciate that a lot, professor.

- Of course, please check when the laboratory is available. You can take the keys from the porter’s lodge. If you encounter any problems, please mention my name. Then, you will get the keys. I, meanwhile, will browse through specialist literature and will try to find some explanations. Maybe someone has already explained an occurrence of similar nature. As for now, I must carefully think through what has happened today.

- Right, professor. Whenever I find a moment, I will come to the laboratory and carry out the experiments again. Maybe I will come up with new conclusions.

For the next couple of days Kamila had little time for deliberations. Nonetheless, while preparing for the next classes, she came across an interesting discovery. If it had not been for her last visit to the laboratory, she probably would not have thought too much of it. However, the events from the recent past had made her more cautious about experiments related to light. Now, she was carrying out an experiment consisting in the examination of the emission spectrum of gases. To her surprise, she realized that there was a formula for the diffraction grating constant, which was identical to the one used in Young’s experiment. The difference was that this time there was no mention of any assumption related to light coherence in the text. Meanwhile, the diagram of the laboratory stand included in the laboratory note only assured her that this was in fact the same experiment (Fig.10)

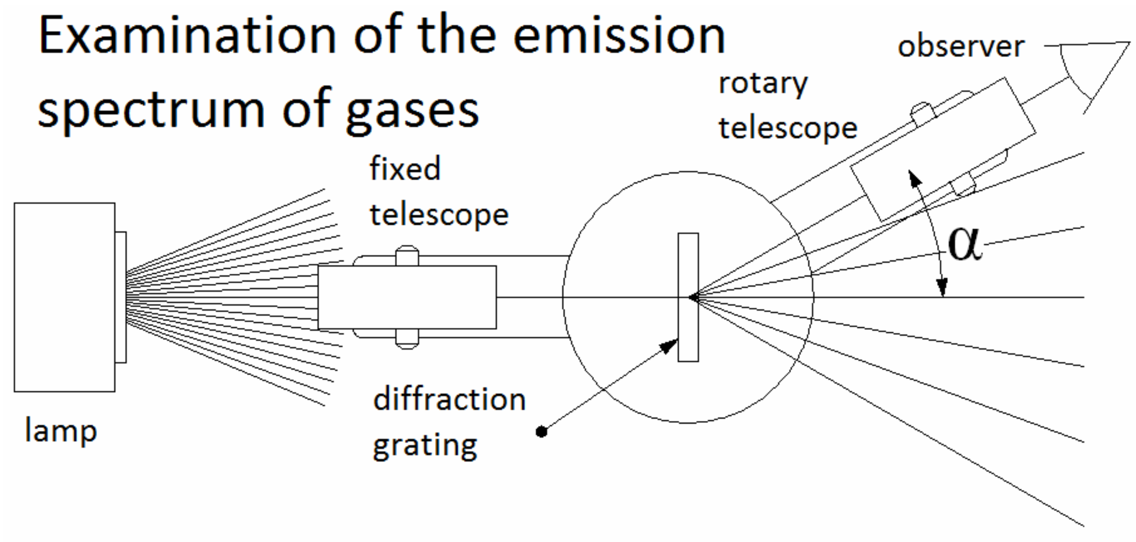


Fig.10 The diagram of the experiment related to the examination of the emission spectrum of gases with the use of a diffraction grating.

The diagram of the experiment did not include the laser as the source of coherent light, but only a fluorescent bulb, which emitted incoherent light. Therefore, she was not surprised that there was no need for the assumption (of light coherence) in order to derive the applied formula. Anyway, the note did not include any derivation for the diffraction grating constant formula. It would be in blunt contradiction with the conducted experiment. At the same time, she realized that the experiment she was going to carry out would essentially confirm her previous observations, namely that in Young's experiment the coherence of light is not necessary. Yet, she started to have some doubts; to what extent is the formula she was going to use in the experiment correct? After all, in order to derive the formula one must make an assumption which in this case is not met. It can mean only two things: the formula is incorrect and it only reflects approximate geometrical dependence measured in this experiment or it is only accidentally correct, but its derivation requires a completely different interpretation, whereby the assumption of coherent light is not necessary. Based on her previous conversation with the professor, she knew that the images visible under the microscope produce similar results with regards to the grating constant as those derived from the measurements of the location of the fringes and supported with the calculations based on Young's deliberations. But was it the correct formula describing the existing geometrical dependence present in this experiment, or only a random similarity with the results of the experiment? Kamila did not know the answer to that question. The following day, making use of a long break between classes, she decided to spend some time in the laboratory in search of new discoveries. She conducted all of the previous experiment once again and she even entered the darkroom where the examination of the emission spectrum of gases is carried out. The conducted experiments did not tell her anything she would not already know, only confirming her previous conclusions. At some point, while she was in the process of watching the 'interference' fringes through the screen grating, she again asked herself the returning question. Why is the image visible on the screen grating the same as the one on the wall? After all, my eyes are not a wall on which I could see light diffused in several places. What I do see, is an image same as the one that I would see on the screen, but, I can see it on the grating. She realized that what she was seeing was the light, which was diffused across various parts of the grating, and which was reaching her eyes from its various areas. Being familiarized, based on the previous diagram (Fig.10), with the characteristics of light passing through the grating she soon found out how to explain the observed images (Fig. 11).

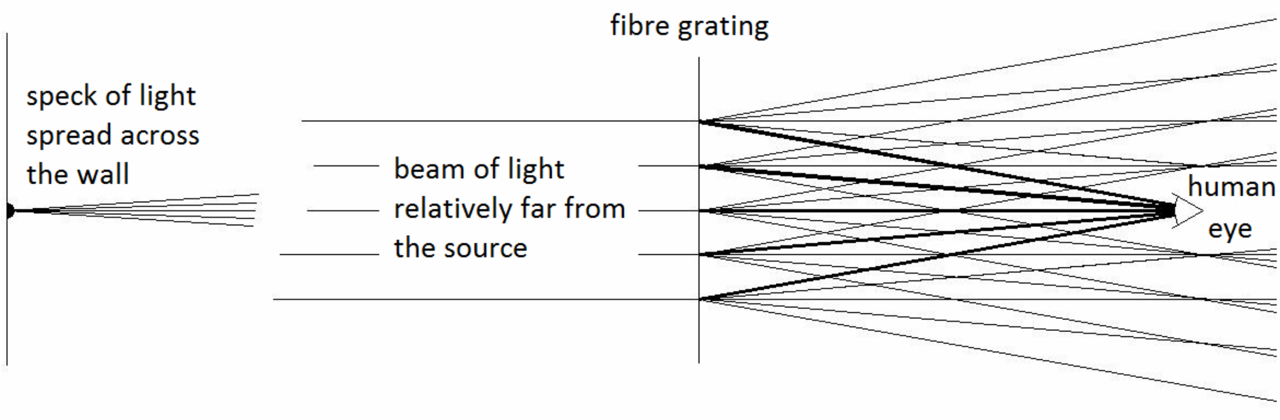


Fig.11 The diagram presenting the mechanism of image creation on the grating.

With regard to those deliberations, one may conclude that the creation of this image is accompanied by the exact same occurrence that could be seen during Young's initial experiment (a subtle decomposition of a light beam falling onto the grating). When the grating is close to the light diffused across the wall, then the light falls onto the grating at different angles. From Young's experiment with the rotating grating, Kamila already knew that if light falls on the grating at an angle other than right angle, then it is diffused at more acute angles (fringes diffused sideways). This may explain why, with the short distance between the spot and the grating, the image begins to blur into one, as it is also the case when the distance between the grating and the screen is reduced in Young's original experiment. The applied interpretation also explains why the observed image changes with the reduction of distance between the eye and the grating. The increase in the distance results in the increased size of the image.

In an attempt to confirm her conclusions, Kamila approached the laboratory table an picked up the diffraction grating, which she was now holding at an arm's length, and not, as previously, close to her eye. Looking through it at a spot light source she could see just one spot. She understood that if the diffraction grating diffuses the light at a more acute angle than the monitor grating and is much smaller, then as a result she is not able to see the other fringes. In order to see them, one would need to have a bigger diffraction grating or to move the one held in the hand a bit to the side. What is interesting, she could see the light on the diffraction grating even though she was not looking directly at the fleck of light on the wall. She realized that her previous conclusions were correct, and the conducted experiment only serves as a confirmation. Light is diffused on the grating in certain directions and that is the reason for the observed occurrence. Playing with the diffraction grating did not reveal anything new in relation to the computer grating. Kamila found out about it while shifting the large grating in such a way so as to see the central fringe not in the middle of it, but close to its edge. Then, she was able to see part of the image. She could not see the part where there was no grating. Within this area there were no edges, which could alter the trajectory of photons. The occurrences observed that day only strengthened Kamila's belief regarding the lack of need for the use of coherent light, however they also did not bring about anything new. So, she again put together the stand where she would be attempting to examine Young's theory and subsequently started to play around with the diffraction grating, moving it closer and further from the screen. Watching on the screen clearly visible flecks of diffused light, moving closer and further away from one another, she noticed that their level of brightness remained constant.

In accordance with a widely accepted wave interpretation, the brightness of a fleck of light must be interpreted as the intensity of a light wave. She then assumed that within a short distance from the apertures, there is an area where light waves coming from separate apertures overlap in such a way that the summation is constructive and therefore a bright fleck might be discerned. However, the final amplitude of such summation depends directly on the amplitudes (intensity) of separate waves. Because the fringes come into existence at a large angle, Kamila assumed that the wave coming from each aperture would also propagate at a large angle. It means that its energy would also have to cover a continually growing area, expanding in proportion to the increased distance from the apertures. Such effect is invariably connected to the decrease in wave intensity as the distance grows and it becomes the more significant the larger the angle of wave propagation is.

The described occurrence should result in a very rapid decrease in the brightness level of existing 'interference' fringes, however that seems not to be the case. A magical shift of energy from one area of the screen where the decrease occurs to the other, where the increase might be observed, is out of the question! Excited about her new discovery, she decided to visit the professor.

In the meantime, the professor had browsed through the quantum mechanics textbook and recalled the assumptions put forward therein. What is more, bearing in mind Kamila's previous doubts regarding the deliberations over a single aperture, he decided to monitor the wave calculations in the case where light from many sources falls on the screen (the infinite number of apertures at a distance heading towards zero). However, it would be much easier to initiate the calculations for the definite number of apertures in such a way as to set their number and distance between them as parameters and monitor the solution (image on the screen) depending on the alterations to those parameters. As a result, he simulated the mechanics of a diffraction grating, where one could assume that the number of apertures on which the light falls is significant, whereas the distances between them are small. The book, as well as the laboratory note, contained an already derived formula for the diffraction grating constant (distance between the apertures).

$$a=\frac{k\cdot\lambda}{\sin\alpha}, \qquad (1)$$

where: k is a number of the consecutive fringe, λ – wavelength, and α – equals the angle at which the observed beam of light deflects on the diffraction grating (Fig. 10).

However, the applied formula does not consider a number of apertures, but only the distance between them. What is more, based on the formula, one may assume that when the distance between the apertures heads towards zero, then sin(α) would have to head towards infinity. So, the explanation he provided during his conversation with Kamila, and based on the very formula, made no sense at all. After a moment's deliberation, he recalled that that was only a rough formula and that it was deduced with only two apertures in mind, not many. On a piece of paper, he drew a diagram used for the purposes of deducing the commonly applied formula so as to take a closer look at the matter (Fig.12).

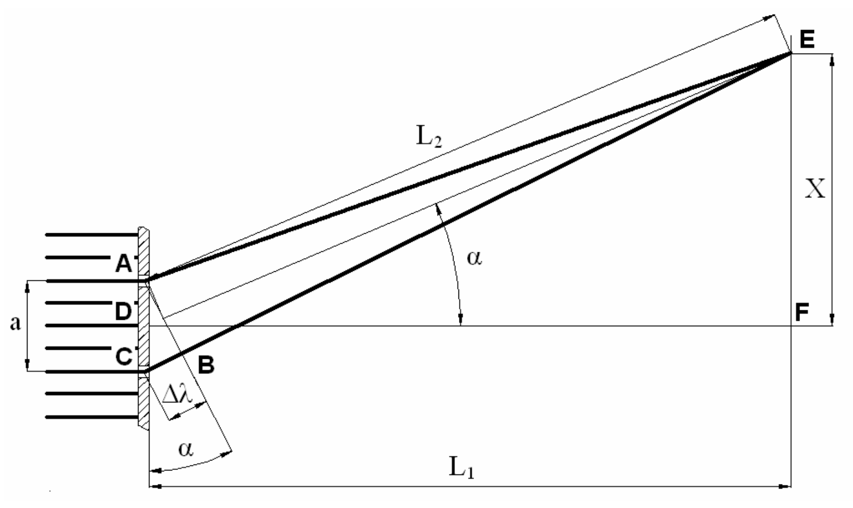


Fig. 12 Diffraction of light on two apertures.

While looking at the drawing one could clearly see that the ABC triangle is a rough imitation of a right-angled triangle. In order to be certain about it, one would have to assume that the distance equals $L_1 \gg a$.
Then the straight lines AE and CE would be almost parallel. For this assumption sin(α) may be defined as:

$$\sin\alpha = \frac{\Delta\lambda}{a} \quad (2)$$

$$\sin\alpha = \frac{X}{L_2} \quad (3)$$

Then, the professor decided to substitute Δλ with kλ as a condition upon which the phase shift produces constructive interference (strengthening) and he was able to deduce formula 1 from formula 2. After a while, he recalled that it was the formula used in the process of defining the diffraction grating constant during the examination of the emission spectrum of gases. Having recalled his previous conversation with Kamila, he also noticed that in this experiment the condition of coherent light was not met and therefore the applied formula had no longer any theoretical grounding. Nonetheless, he still had some reservations, because in the experiment in question one also made use of the aperture. So, before reaching the diffraction grating, light first passes through the aperture, whereby it may be assumed, based on the wave interpretation, that it leaves as coherent light. Having observed that, the professor decided to carry out more accurate calculations for the wave model, without worrying too much about meeting the condition of light coherence.

Of course, he could also attempt to combine formulas 2 and 3 and, with the use of the Pythagoras theorem, deduce a well-known diffraction grating constant dependence, which is commonly used in the laboratory seminars devoted to the subject. But, being aware of the assumed approx. quantities, he decided to carry out numerical calculations. The computer may as well calculate the accurate route covered in relation to multiple apertures. {He thought} Then, it would be possible to accurately sum up all of the waves reaching the screen, while bearing in mind the phase shift calculated separately for each aperture, without having to resort to approximations. Creating a relevant application did not take long. Having derived the following data:
L_1 = 1,5m, a = 5μm and λ = 632,8nm (corresponding with the diffraction grating experiment), he got the following result (Fig.13).

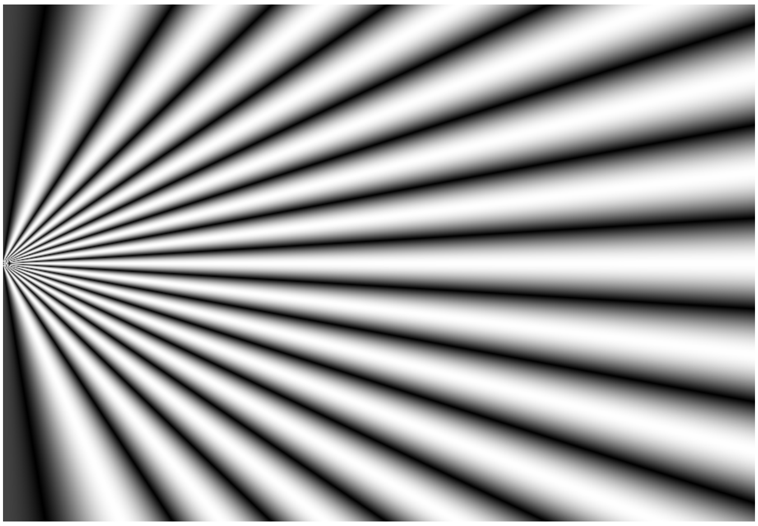


Fig. 13 The decomposition of light for the wave simulation of Young's experiment for two apertures (seen from above). The horizontal axis reflects the distance from the diffraction grating.

Based on the conducted simulation, he could clearly see that the beams of light leaving the grating are much wider than what was observed in the experiment. However, knowing that the simulation had been carried out for only two apertures, the professor was not surprised with the result. After all, the real image for two apertures contains fringes located close to one another. The professor explained the excess of side fringes in the simulation with the fact that in the actual diffraction the intensity of light does not decompose in the same way in all directions and is subject to change proportionately to the distance. However, he did not take that into consideration in his simulation. Had he done that, {he thought}, he might have expected a decreasing intensity of brightness for the distant fringes. Satisfied with the results, he conducted further simulations for a growing number of apertures (Fig.14).

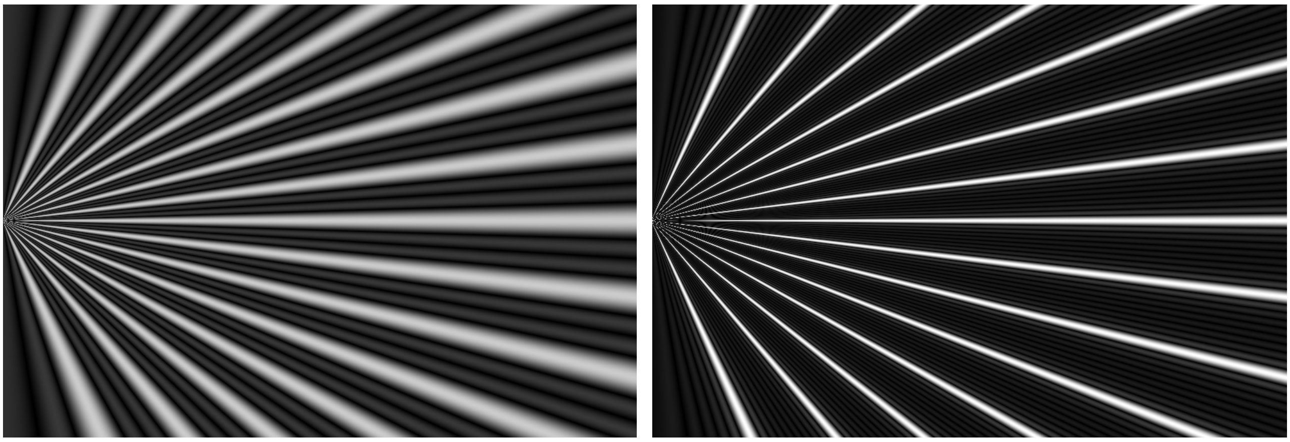


Fig. 14 The decomposition of light for the wave simulation of Young's experiment for five and ten apertures (seen from above). The horizontal axis reflects the distance from the diffraction grating.

After analyzing the conducted simulations, the professor realized that the position of individual fringes does not depend on the number of apertures. However, the width of the interference fringes seen on the screen should be largely dependent on this parameter. The more apertures involved in the transmission of light, the narrower should the fringes become. Professor's further deliberations were disrupted by the sound of someone knocking at the door. It was Kamila who entered the office with confidence, and announced that she had been to the laboratory and found yet another inconsistency between the theory and the actual experiment.

The professor gave out a little smile and greeted his guest.

- Good morning, Ms Kamila.
- Good morning, professor. That, right there! It is very similar to the diagram from the laboratory note. Is the depiction of Young's experiment? { She cast a quick look at the screen}
- Yes, I have prepared a simulation, and at the moment it almost completely reflects the experiment. What brings you here today?
- I have recently visited the laboratory and conducted a few experiments. I've come to ask a few questions regarding them. But first, I would like to mention that while I was preparing the stand to conduct the experiment entitled *The examination of the emission spectrum of gases* I noticed that it was exactly the same experiment as the one carried out by Young. The only difference being that in this experiment one makes use of a fluorescent bulb as the source of light instead of a laser. The formula applied in this experiment is exactly the same as the one used in Young's experiment, however the condition of light coherence is not met. So, I am not entirely sure to what extent I might rely on the dependence, assumed in the experiment, between the grating constant and the angle at which a certain color can be seen. Nonetheless, it confirms the previous conclusion that coherent light is not required in the case of Young's experiment.
- But Ms, maybe you didn't notice that there is a diaphragm on the diagram of this experiment. Of course, the source of light used in the experiment is completely incoherent in all of the aspects

discussed previously, but before it reaches the diffraction grating it must first pass through the aperture. Therefore, in essence, there is no problem because light, in accordance with Young's deliberations, becomes coherent after passing through the aperture.
- However, professor, I kept all of the above in mind and I have already not only thought it through, but also checked it. First of all, following Young's interpretation, light, after passing through the aperture, produces a spherical wave, not fringes. As we have discussed, this stands in contradiction with the experiment. Second of all, in order to be correct (obtaining a coherent beam of light after passing through a single aperture) the formal size of the aperture would have to be at least comparable to the wavelength. It is exactly at this point that I can't agree with your reasoning, because during my previous visit to the laboratory I conducted the experiment in question, altering the size of the aperture placed behind the source of light. Of course, in the case of a narrow aperture one can discern colourful fringes seen at different angles. But, those fringes are very narrow. While I was turning the knob adjusting the aperture, the fringes were becoming wider. Finally, I increased the size of the aperture to the max. It was approx. 5mm. The fringes seen through "the telescope" also became wider, reaching approx. 5-6mm. So, the fringes I could see were as wide as the opening of the aperture. The fringes are also present without the aperture, however they are respectively wider, because the light falling on the grating may be characterized by an even larger section. As a result, I concluded that the width of the observed fringe in the mentioned experiment depends on the width of a light beam falling on the grating. Then, it is safe to say that the clearly visible fringes may be observed even when the aperture is so wide that it is no longer viewed as such and can't be regarded as the source of coherent wave. Particularly, when we realize that the 'fringes' are also visible when the aperture does not exist in the formal sense! As a matter of fact, you have also forgotten about our previous discussion on the number of incoherent photons present between the edges of a single aperture, when incoherent light falls on it. And in this case, I am talking about the aperture as wide as 5mm! Thirdly, even if we assume that light becomes coherent after passing through the aperture, then it is still coherent only in space, not in time! We need to keep in mind that certain areas of the screen (eye) are simultaneously reached by a number of photons emitted at different points in time.
- If what you are saying is really true, then the experiment related to the examination of the emission spectrum of gases constitutes yet another proof that there is no need to use coherent light in Young's experiments. Then, the formula applied in this experiment would have to be derived with different theoretical assumptions in mind. Additionally, the assumption of at least local coherence of light for the incoherent light beam would not hold out against the argument of time incoherence. In such case, both temporal and spatial coherence of the light beam falling onto the diffraction grating is required.
- I thought so. Of course, at the moment I have no idea how to come up with a different explanation, and following up on that, how to derive the dependence described in textbooks. As for now, I assume that the mentioned dependence (1) is correct regarding the quantitative aspect. However, it does not change the fact that at some point in the future it would have to be derived for the assumptions that, as I imagine, would not be so easily contested.

Kamila, while looking around the room, noticed an open physics book, which was lying on the table.
- Here! This book describes the experiment similar to the one I was conducting during the classes. What is this book, professor?
- This is the quantum mechanics textbook. I am aware that you have not yet been introduced to this subject during the course of your studies. In the following terms you will become familiarised with this subject in depth, as it constitutes the ground for understanding the premises of present day physics.
They sat at the table, where the open book, previously browsed by the professor, was lying.
- Would it be possible for me to borrow this book?
- I can't see why not. However, it would be good to first acquire some basic knowledge of the subject. Especially mathematics. Without that, it will be almost impossible to pass this physics

course.

- I understand.

- The introduction, where Young’s experiment is discussed, does not contain any advanced concepts in the area of mathematics. The chapter entitled ‘Particles and waves’ is devoted to the theory of the so-called wave-corpuscular duality. In quantum mechanics, it is assumed that each solid particle may be assigned to a wave, i.e. a matter wave. I reckon that you are well aware that in classical physics one assumes that matter consists of well-defined solid particles. Those have defined mass, location, momentum and energy.

- Yes, I remember. In the mechanics class we were attempting to establish the momentum, location and trajectory of a bullet which was represented by a solid point. The lecturer mentioned that all of those parameters are always well defined in classical physics and, at least in theory, they may be defined with any accuracy. What is a matter wave? I have never come across this concept.

- Of course, that’s true for classical physics, however not in the case of quantum mechanics. Before we begin to discuss the concept of matter waves, it is good to first take a look at some historical facts. As you remember, James Maxwell described light as an electromagnetic wave. Before him, other prominent scientists, such as Young or Frensel, also thought of light in the category of wave, however it was Christian Huygens and Robert Hooke who first challenged Newton about the nature of light. Newton’s prominence was so great that, for a long period of time, only his point of view was widely accepted, whereby the assumption was made that light is a type of particle viewed in a similar way as other solid objects. At the time, many simple occurrences could be interpreted by referring to both wave and particle interpretation. Only the attempts to measure the speed of light swayed the scientists towards wave interpretation. Thomas Young’s experiment served as another significant factor which facilitated the assumption of wave interpretation as a reflection on the nature of light. It was because Young interpreted his experiment by referring to the phenomenon of diffraction and interference, which are present in wave occurrences, and then combined different geometric quantities present in this experiment. No one at the time knew how to explain Newton’s ‘particle’ interference. Therefore, his wave-corpuscular hypothesis was forgotten until the arrival of Max Planck. Planck, while looking for a formula that would rightly explain the emission spectrum of a blackbody, had to make very bold assumptions in his deliberations at the time. Namely, he assumed that light is emitted in portions, each with specific energy. It would all be alright if not for the fact that his hypothesis implied the existence of light in the form of separate portions of energy (which was closer to wave-corpuscular hypothesis) but also resulted in the derivation of a formula which described experimental data. So, it was the first departure from the dominant position of light wave interpretation. Planck’s hypothesis was ignored by his contemporaries and treated mainly as an inconvenient mathematical trick useful for the derivation of a correct formula but having no impact whatsoever on a commonly accepted interpretation of light as a wave. Maxwell’s wave interpretation was still intact. However, only a bit later, in 1905, Albert Einstein proved in his photoelectric experiment that Planck was right after all and that light is in fact comprised of accurately defined portions of energy. Then, it was no longer just a mathematical trick, but a concrete, almost parallel experiment, which in no feasible way could be reconciled with Maxwell’s theory. Later on, it was Arthur Holly Compton who caused similar turmoil by concluding, in the process of examining X-rays decomposing at different angles, that light may be characterized not only by a defined portion of energy, as proposed by Planck and Einstein, but, as is the case with solid particles, also momentum. At present, it is assumed that light is made of the so-called photons (light particles).

- Why then do we still learn at school that light is a wave?

- The experiments conducted by the mentioned scientists could have completely undermined wave interpretation as early as the beginning of the XX century if it hadn’t been for Young’s experiment and others of a similar nature, e.g. Fresnel’s experiment, which is still said to focus on diffraction and interference. Moreover, the problem also lies in the existence of the so-called electromagnetic waves (radio, microwaves, etc.), which seem to be the same as visible light and which, however, are much harder to explain based on the concept of particle.

- That's true. It is impossible to claim that radio waves don't exist. After all, radio, tv (not cable television), cell phones, etc. are in use nowadays.
- That's the point. What's more, most deliberations regarding light are based on the assumption that it has no mass, which also fits in perfectly with the wave standpoint. Only Einstein's theory of relativity makes it possible to assign relativist mass, related to the photon energy, to photons. Which may serve as a perfect explanation for the so-called Compton's effect, i.e. the fact that photons have momentum (and therefore should also have mass!).
- So, I understand that wave-corpuscular duality related to light means that light is a wave and at the same time isn't. It makes no sense!
- Not only for you. In reality, it is very difficult to find common ground between the wave interpretation and the wave-corpuscular one so as to make it into a theoretically and logically coherent argument. In truth, I don't even know if that's possible. At the moment, it is commonly accepted to refer to both wave and wave-corpuscular interpretation depending on the situation. Here, it is common to refer to the concept of formalism in mathematics which allows us to shift between both interpretations.
- But I still can't wrap my head around this idea. I recollect from our classes that the wave is nothing else but disruption of the medium moving in space. Whereas wave-corpuscular interpretation is all about 'light' bullets moving in space. Let's call them photons. Those two make no sense together.
- Exactly. As you have already mentioned, a wave is viewed as a disruption to the medium that moves in space. In the case of a well-known occurrence, such as sound propagation, it is the gas or solid body atoms that constitute a disruption to the medium. In the case of light, which travels easily in a vacuum, it was however almost impossible to define the medium. Therefore, Maxwell and previous scientists assumed the existence of a hypothetical medium, which they then called *ether.* Maxwell's theory came to life as an attempt to define the compressibility of that hypothetical medium and is based on the premise of its existence [5]!
Then, as part of the research regarding the concept of *ether*, Albert Michelson and Edward Morley carried out a series of experiments which dispelled our illusions regarding that hypothetical medium. At the moment, the concept of *ether* is not taught at schools because it is deemed to be incorrect.
- With all due respect, if Maxwell's theory assumes the existence of *ether* for the purposes of electromagnetic waves propagation, then why is it still considered to be correct?
- Of course, initially Maxwell's theory was dependent on that assumption and, to be perfectly honest, it still is. Nowadays, it is believed that, regardless of matter, there might be electric and magnetic fields in space, which then have an effect on it. Therefore, it is possible for a so-called electromagnetic wave to travel through a vacuum. In Maxwell's theory it was different states (mechanical) of *ether* seen through stress and movement of the medium. Whether we would see it as magnetic and electric field describing the electro-magnetic state of a certain point in space (field theory), or the mechanical state of *ether*, then, from a mathematical standpoint, it would still be the same. The only variation would be visible in applied terminology. Maxwell's theory has survived only thanks to the usefulness of the formulas related thereto. By the way, most of the formulas applied there were not derived by Maxwell himself. His main achievement was the fact that he was able combine the work of other scientists and transform it into a coherent concept.
- All of that is really interesting, however at the beginning of our conversation you said something about the waves of matter. I still don't understand what those are.
- Right, I have already forgotten what I have started with. As you have probably already realized the question of *what is light?* has not been solved yet, because it is difficult to comprehend that something may be seen both as a wave and matter and, more to the point, that it might have no mass (at present interpreted as rest mass). But, to make things even more interesting, George Thomson made an amazing discovery proving that interference fringes exist also for such objects as electrons.
- How is that even possible? Electrons can interfere? {Kamila twitched with surprise} What did those experiments consist in?

- As you know, in Young's experiment, a beam of light is transmitted through a diaphragm with two apertures.
Then, specific fringe images appear on the screen which are interpreted as interference images. When instead of photons one transmitted molecular beams (ions, electrons, protons, etc. travelling in one direction) through crystal glass, then on the screen comprised of special detectors one could also notice structures similar to interference fringes. Of course, the observed occurrence was of great surprise to the scientists who were not able to come up with a rational explanation for the observed effect in relation to objects which could not be treated as waves from a classical standpoint.
- I think I am beginning to understand. Since it has been assumed that light is a wave, which sometimes must be treated as particles, then the corpuscular matter is on occasions also treated as a wave. As a result, the matter interpreted as a wave is often described as a wave of matter.
- Exactly. Moreover, this interpretation was also very convenient. One may say almost essential for the newly rising concepts of quantum mechanics at the time. Niels Bohr posited that the moment of momentum for separate electrons in the atom is quantized. Such assumption allows for an accurate reconstruction of the emission spectrum of gases which you have recently examined in the laboratory.
- How so?
- It results from the fact that the electron may be viewed as a wave which on individual orbits must create a standing wave so as not to reach the zero mark. It was discovered that such condition can't be met in the case of random distances between the electron and a positively-charged nucleus. On application of a few additional postulates, the physicists managed to relatively accurately describe various energy levels that the electron may assume with regard to various atoms. Assuming that the energy of both emitted and absorbed photons depends on the difference between calculated energy levels, it is possible to define the wavelength (color) that would have to be emitted by, e.g. a hydrogen atom. The Bohr model was not initially accepted on the basis of its exaggerated simplicity, but the principal postulate to view matter as the wave of matter became the foundation of quantum mechanics.
- That's amazing! {Kamila gasped with excitement} I can't wait to read this book. Would it be possible for you to lend me the book, professor? Please.
- Ms, please, don't get carried away. At first, I would recommend that you read about the history of physics. It will be as compelling. Once you have participated in a more advanced mathematics course, then you can familiarize yourself with more challenging concepts.
- At the beginning, you mentioned that you'll tell me how quantum mechanics explains Young's experiment.
- Right. As usual, I got sidetracked. What was I about to tell you? Oh, yes. In the chapter entitled 'Particles and waves' one may find an experiment which allows physicists to believe that wave-corpuscular duality really exists. Since Young's experiment turns out to be successful with regard to matter particles, and that is to say in relation to all beings of the corpuscular nature instead of the wave one, then one could also attempt to dismiss the wave interpretation with regard to the original experiment with light. Throughout history, it would sometimes happen that first fringe images were observed in the experiment with light. So, as a result, it was easier to acknowledge the wave interpretation. Only after a while was it discovered that the same occurrence exists for matter particles. Therefore, the previous interpretation was used so as to explain the newly discovered experiment. And what would have happened if the order of those discoveries was different?
- Interesting, I haven't thought about that. I assume that regarding the experiment with a stream of electrons diffused in the apertures, a purely corpuscular explanation would be found. Then, Young's experiment with light would be regarded as a proof that light also possesses only corpuscular characteristics.
- Exactly. You can see now how important the order of discoveries and the ideas that follow really are. The way we perceive what we see shifts and it shapes the way in which we interpret new discoveries. So, to substantiate the claim that a material object might be both a particle and a wave,

the following experiment is presented in various books. The professor took out a pencil and copied a diagram from a quantum mechanics textbook, showing the results of light being transmitted through a diaphragm with two apertures (Fig.15).

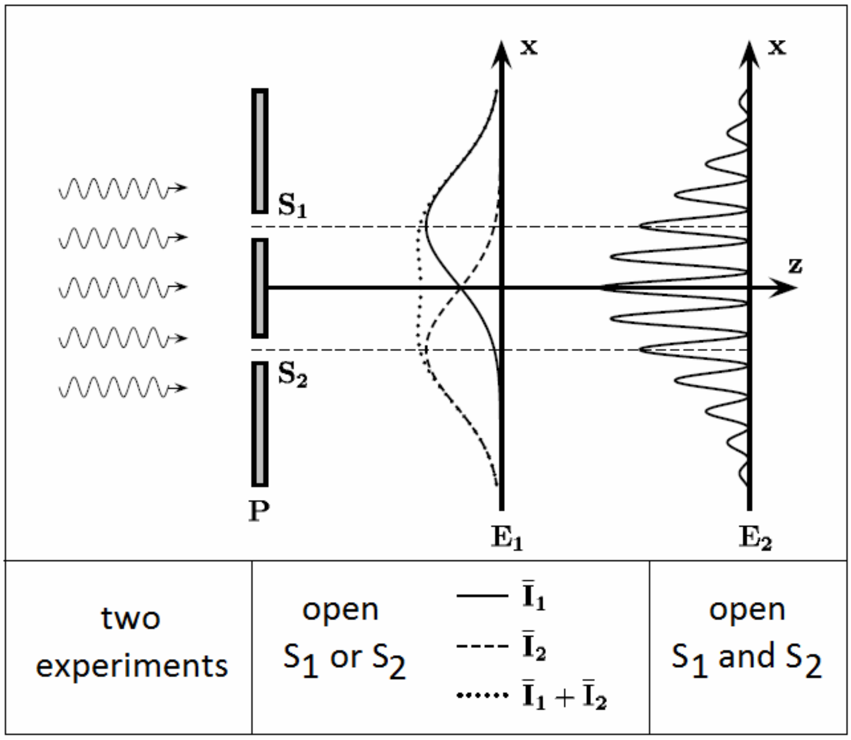


Fig. 15 Diagram of two diffraction and interference experiments on two narrow apertures meant to prove the validity of wave-corpuscular duality discussed in the quantum mechanics textbook [2].

- What are those curves, professor? This sinusoid with variable amplitude surely represents the fringes seen on the screen in Young's experiment.
- That's true. But what's most interesting about this experiment is the image created after passing through the single aperture. The centre image presents light intensity curves, or the molecular stream falling on the screen (in the experiment with electrons, etc.), coming not from two but from a single aperture. The continuous curve represents the propagation of light coming from the top aperture, whereas the dotted curve, the same process but in relation to the bottom one.
- I understand that such propagation is explained as a consequence of light's corpuscular nature.
- Indeed. It is assumed, that photons passing through the aperture hit the side of the edge. Then, such randomly propagated photons continue to move at a slightly different angle, creating a broad image of the aperture on the screen. Of course, the image for the second aperture is slightly shifted with regards to the image created for the first one.
- And what would happen if both apertures were open? I guess, then we would get a classic example of Young's experiment and a fringe image on the wall, which may be seen on the graph to the right.
- Exactly. One wide, blurred image is seen as the result of the corpuscular nature of a stream, e.g. of light, used in the experiment. If we assumed the same line of reasoning with regards to two open apertures (corpuscular view), then we should expect to get the image similar to the dotted line in the centre. However, the experiment shows that it is the fringe image that is created, just as the one presented in the graph on the right-hand side. The result may be conveniently explained as the aspect of the wave nature of applied beams: of light or matter, e.g. electrons. It stems from the simple fact that in order to substantiate the obtained result, we refer to the phenomena of diffraction and interference.
- So, we will get the same result as the one I got in the laboratory while carrying out the experiment

with two apertures and a laser?
- Yes, indeed. Because, while examining light, at one stage we must draw on the premises of the wave nature of light, whereas at other one is likely to refer to its corpuscular characteristics. Therefore, it is viewed as a proof for the validity of the wave-corpuscular duality. Moreover, it is also true for material particles, which are sometimes viewed as waves.
- That seems to be pretty complicated. I still can’t imagine how material particles could be viewed as waves. Can I take one more look at the picture?
- Of course, here you go.
Looking at the diagram drawn by the professor, Kamila was trying to recollect what she saw in the laboratory while she was conducting similar experiments on her own. Suddenly, it struck her and she let out an unintentional scream.
- It’s all a pack of lies!
- Excuse me?! {Responded the disgusted professor}
-Oh, I’m really sorry. Please, forgive me for my behavior. There is something I don’t understand, though. Please, take a look at the centre of the diagram. Light passing through a single aperture does not create the same image as the one that can be seen here. I am certain that while I was letting a beam of laser light through a single aperture I got a fringe image as a result. It was around the same time you were, rather puzzlingly, trying to explain that to me by referring to the infinite number of apertures located at zero distance.
- Hm…, yes, that’s true. Today, I have even prepared a simulation to see how the image would react if I changed the parameters such as the number of apertures and the distance between them. Why didn’t I see that before?! {He shouted excitingly} How could I be so blind that I didn’t notice it before! Indeed, light passing through a single aperture creates a fringe image, contradicting everything that is said in the textbook [2]!
In the laboratory classes I show my students that light passing through a single aperture creates a fringe image. And here I am, contradicting myself by saying something completely different!
- If light does not react in the way presented in the textbook, then the conclusions drawn from those deliberations are false. Aren’t they?
- Yes, of course. But why at the very beginning of a highly renowned textbook one comes across such a significant error?
Is it possible to obtain the exact same image on the screen as the one presented in the diagram?
After all, quantum mechanics is not researched by dumb people who wouldn’t notice such a glaring error! Why don’t we refer to a different physics textbook entitled *The Feynman lectures on physics* Vol. 1.2. In the chapter entitled *Quantum effects* one comes across a description of three similar experiments: with bullets, waves, and electrons. In the first experiment, Feynman describes the test (never carried out according to the author) with a machine gun shooting bullets towards an armor plate with two apertures. On the screen, behind the obstacle, the bullets reaching a given point on the screen at a certain time are counted.
Next to the diagram, Feynman presents the hypothetical result of such experiment (Fig. 16) [3].

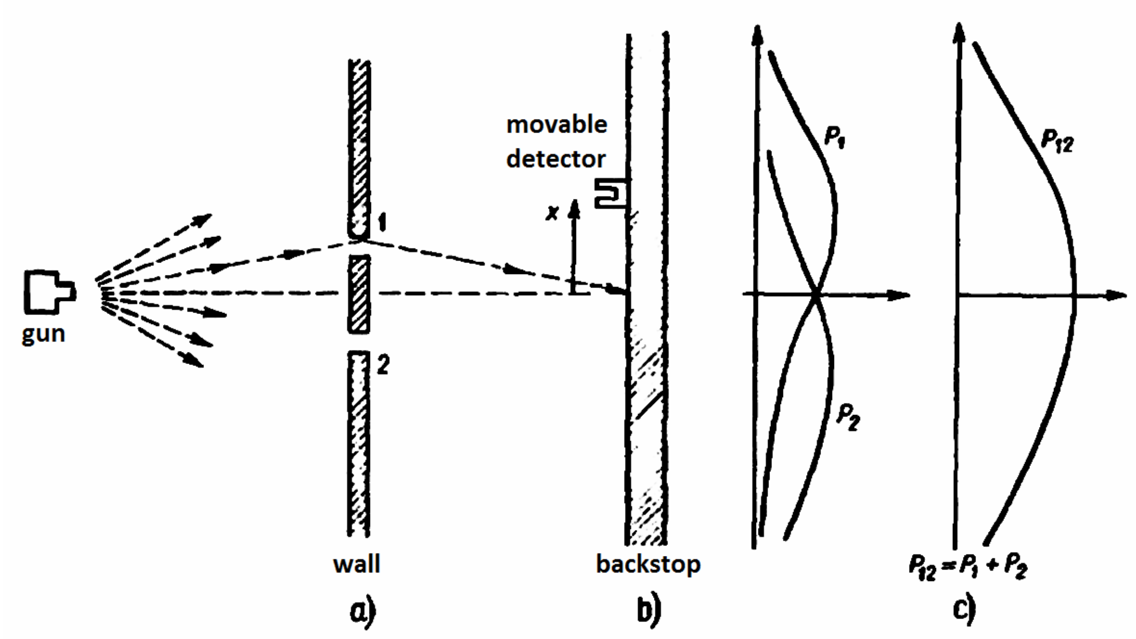


Fig.16 The experiment with bullets passing through an armor plate with two apertures that the bullets pass through [3].

- I understand that such reactions may be expected for purely material objects?
- Indeed. Then, Feynman presents the second experiment with waves (Fig. 17).

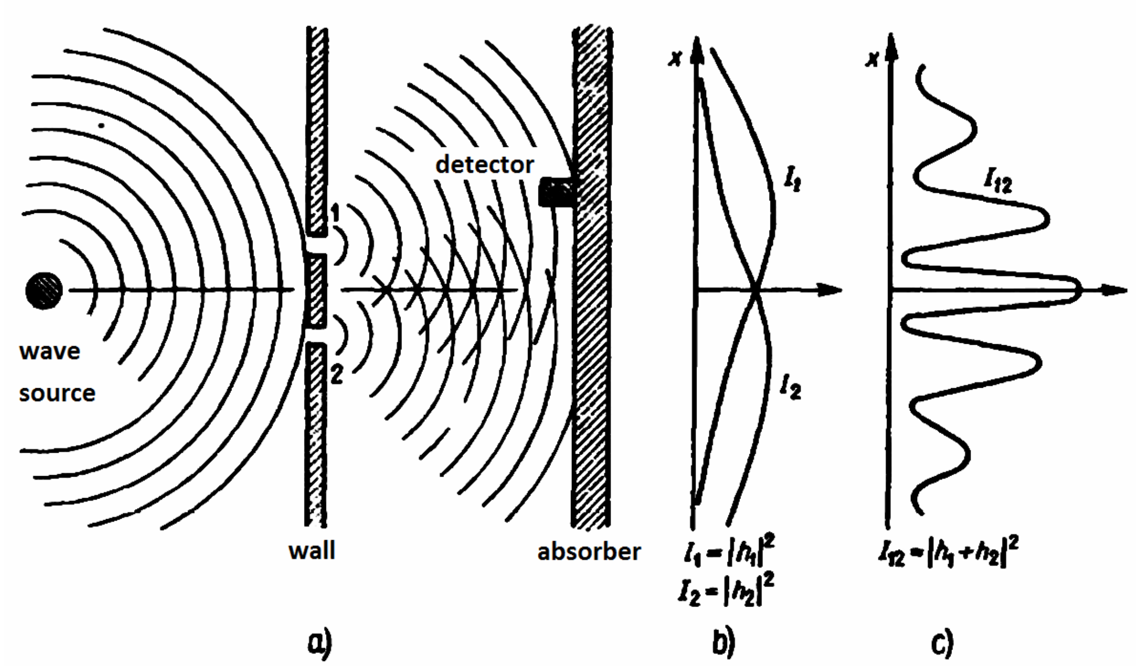


Fig. 17 The experiment with water waves passing through a diaphragm with two apertures [3].

- Right, but in this case the author assumed that the wave source is selected in such a way as to have the same phases on both apertures. Anyway, I remember from our lectures that there was a similar experiment showing that a mechanical wave reacts on the apertures in the same way as presented in the textbook [3]. Therefore, the results of the mechanical wave experiment presented here are in

line with that experiment. Of course, it's only natural to assume that in relation to different and randomly changing phases on both apertures we won't be able to get the same image as presented in the diagram on the right-hand side.
By the way, the presented image related to light is in contradiction with the experiment, because a single aperture would be enough to obtain fringes on the screen!
- Indeed, light reacts in a different manner. However, in his textbook, Feynman describes the case of light passing through a single aperture. Later, we will check more carefully what explanation he provides. Right now, let's take a look at the next experiment. This time with electrons (Fig.18).

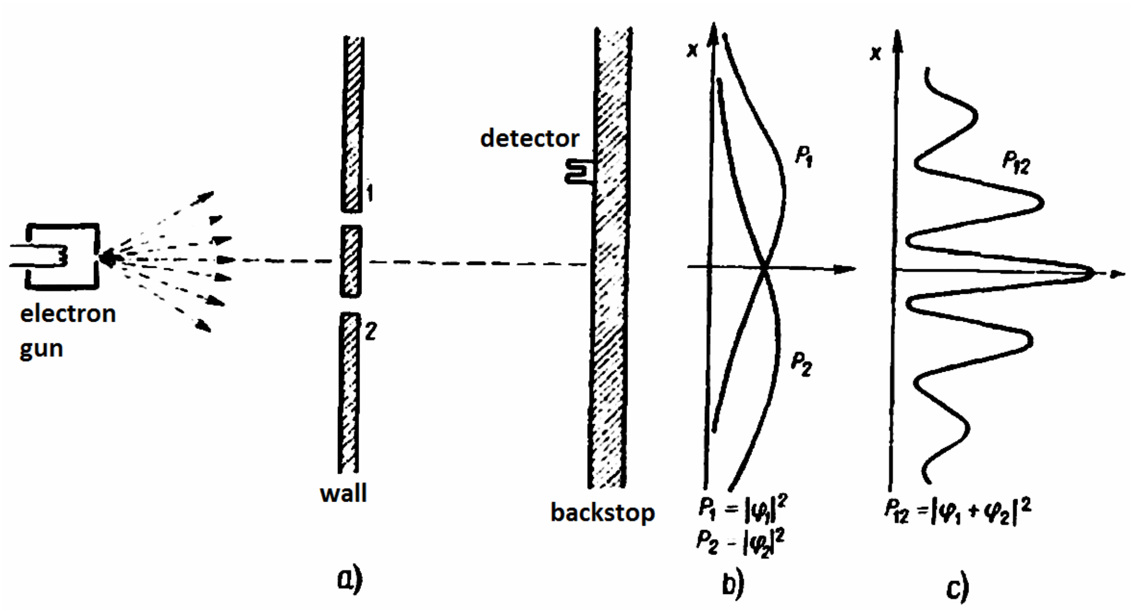


Fig. 18 Experiment with electrons passing through a diaphragm with two apertures [3].

- In fact, it's in line with the theory that Mr Kryszewski puts forward in his textbook [2]. In the case of a single aperture, one gets a flat wide image. Whereas, with regards to two apertures, one gets a fringe image. However, in this instance Feynman does not mention light but goes straight to the description of electrons.
For instance:

The first thing we notice with our electron experiment is that we hear sharp "clicks" from the detector (that is, from the loudspeaker). And all "clicks" are the same. There are no *"half-clicks."*

We would also notice that the "clicks" come very erratically. Something like: click ….. click-click … click …….. click …. click-click ….. click …, etc., just as you have, no doubt, heard a geiger counter operating.

- So, one may conclude that only entire electrons may be measured, but then, how can they interfere on the screen? There must be a different reason and it probably has something to do with the apertures.
- Not necessarily, Ms Kamila. Feynman describes the results of the experiment where the electrons pass through a single aperture, which is very similar to what we can see in relation to material particles and does not seem to raise any doubts, as well as the results for the passing of electrons through two apertures. In the second case, what we get is a fringe image which corresponds with a wave image and leads us towards the interpretation based on wave interference:

Let's now try to analyze the curve in fig. 37.3 (Fig.18) and find out if we can really *understand the reactions of electrons. Particularly, one is tempted to say that…*

- This is why one refers to the concept of wave-corpuscular duality that I mentioned before. Especially, when we realize that, with regards to light, we are also able to get 'entire' photons for a particular colour, and not just half of a photon. So, as it was in relation to electrons, the entire click-click, and not just a half click.
- I am sorry, professor, but what kind of click-clicks is he writing about? What electron reactions with regard to this particular experiment is Feynman writing about, if right next to it, in his own book, he states that:

We should say right away that you should not try to set up this experiment (as you could have done with the two we have already described). This experiment has never been done in just this way. The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in. We are doing a "thought experiment," which we have chosen because it is easy to think about. We know the results that would be obtained because there are *many experiments that have been done, in which the scale and the proportions have been chosen to show the effects we shall describe.*

{Indignant at what she has read, Kamila continued}

- If the author claims that the experiment has never been carried out, then what right does he have to discuss the results of such experiment and, even worse, assume that the course of such experiment would be just that? As though he was the one conducting it. Based on the provided results of the experiment, he draws controversial conclusions regarding the nature of electrons, even though *[The] experiment has never been done in just this way.* To make things even worse, the author states that *should not try to set up this experiment*. So, according to Feynman, it is not only that one shouldn't carry out this experiment, but that one shouldn't even try! However, he is the one who forces on us the only correct interpretation of the experiment that has never been carried out. The one that, incidentally, sits well with his deliberations. Of course, the author also refers to other experiments (though, he doesn't name them), but those must certainly be indirectly linked to the matter and therefore less credible in attempts to prove the thesis behind the wave nature of electrons, and, as result, his point of view.
- Please, Ms Kamila, stay calm! Mr Feynman wrote his book a while ago. It is possible that while he was working on his book, the experiment had not been carried out yet. It's been a while since the book was published and it's likely that this part is not valid anymore. It needs to be confirmed, though. Then we would get a clearer view of the matter in question. However, I must admit that the author's line of reasoning is hardly factual and brings his name into disrepute. Describing the experiment that has never been carried out as if it had been done by the author himself, as well as quoting the results of the said experiment in order to substantiate one's doubtful conclusions is rather reprehensible and unacceptable. Therefore, it is even more surprising that the author admits that in his own book. It's surprising really that he didn't exercise more self-control over his writing. After all, we are talking about a highly intelligent person. It might be that he was so certain of the validity of his assumptions that he decided to risk his reputation.
- Strange, indeed. After all, this part of his book, because of the mentioned excerpt, could make many readers smile pitifully. At least, with regard to this man's intentions. It is possible that Feynman deeply believed in what he was doing and teaching. Even though a strong belief of a renowned specialist in his convictions may lead many people towards them, sheer belief per se doesn't make those convictions true. And referring to the experiments that have never been carried out should always set off an alarm in our head not to accept the author's convictions at face value and based only on his alleged position of authority.
- That's the right approach, Ms Kamila. However, let's get back to the beginning. The experiment in question was meant to depict the behavior of not only particles (electrons in this case), but also of

photons after passing through a single aperture, as well as two apertures. All in such a way as if the electron or photon could pass simultaneously through two apertures. You have noticed previously that, in the case of light, we will not get the same image as the one presented in the textbook. Why then do the books contain information that is in contradiction with what can be observed in the laboratory? Once light has passed through a single aperture, is it possible to obtain a single wide image without side fringes?

- Maybe, we should first ask what is the feasible difference between the aperture found in our 'school' experiment and the one characteristic of a professional experiment since both results are so different?

- The aperture will always be viewed as one and from the standpoint of wave deliberations one does not refer to the shape and material that it is made of. So, there is no difference, it there?

- I guess not. {Kamila responded hesitantly} If the shape of the aperture is not taken into account in other discussions, then the reason for discrepancy must be found somewhere else. In what other way can our aperture differ from others? There seems to be no significant difference. {She stated after a while}. The environment around the aperture changes, though!

- How so? {Said the surprised professor}.

- In the experiment that you've described there is one more diaphragm with two apertures. In order to obtain a good interference image, one must place such apertures as close as possible to each other. So, if we want to carry out the experiment with a single aperture, then we must first cover the second one. Therefore, in the vicinity of the uncovered aperture there is an additional edge which may have an impact on the created image. In our experiment, there is no additional edge close to the aperture.

- Brilliant! {The professor burst out with excitement} It's that simple! Let's go to the laboratory and test your idea.

The stand preparation did not take long and they soon obtained the result that was not at all surprising to them (Fig. 19).

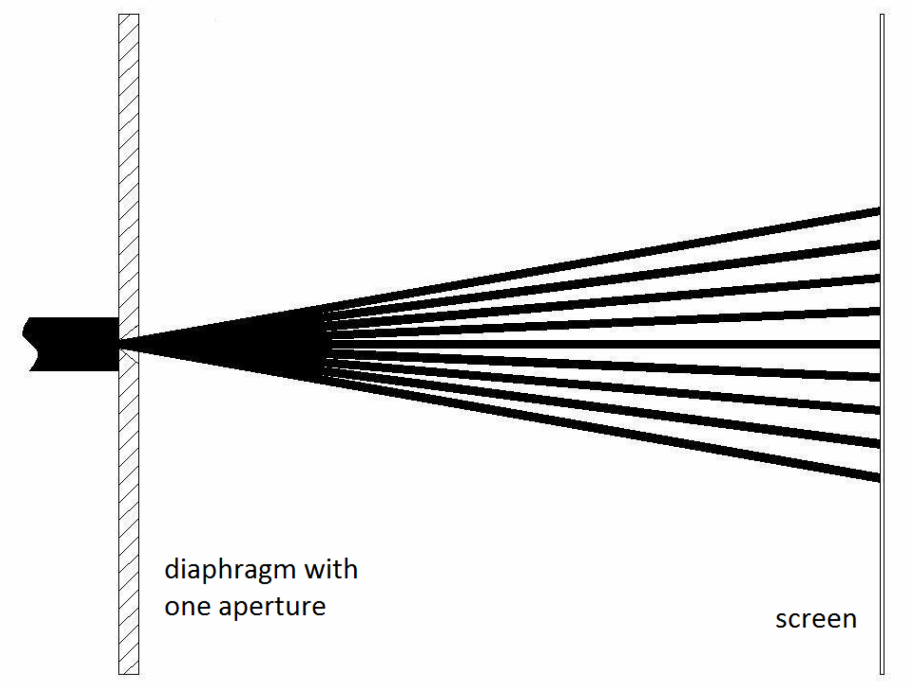


Fig. 19 The propagation of light after passing through a single aperture.

That is how they made sure that the book contained a serious error. A single aperture creates a fringe image. Then, Kamila held a thick piece of paper towards the aperture in an attempt to cover it with an additional diaphragm (Fig.20).

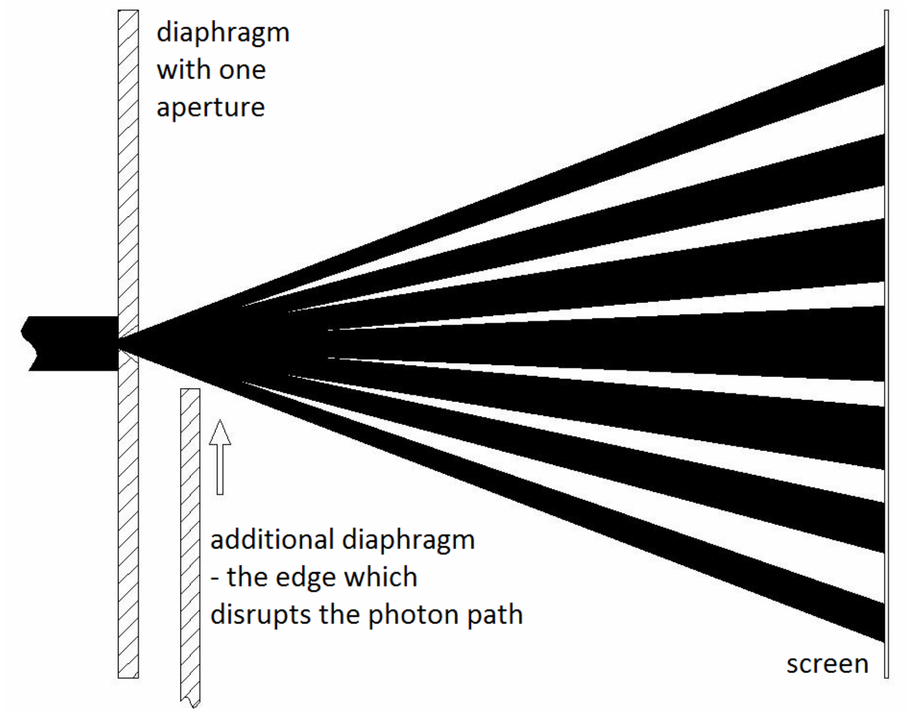


Fig. 20 Young’s experiment with a single aperture disrupting the path of photons with the additional edge. In this case, the fringes are flattened and shifted sideways.

What they saw was new to them. When the edge of a piece of paper was getting closer to the aperture, the fringes on the screen would shift sideways and become blurred at the same time (the width of individual fringes would grow, Fig.21).

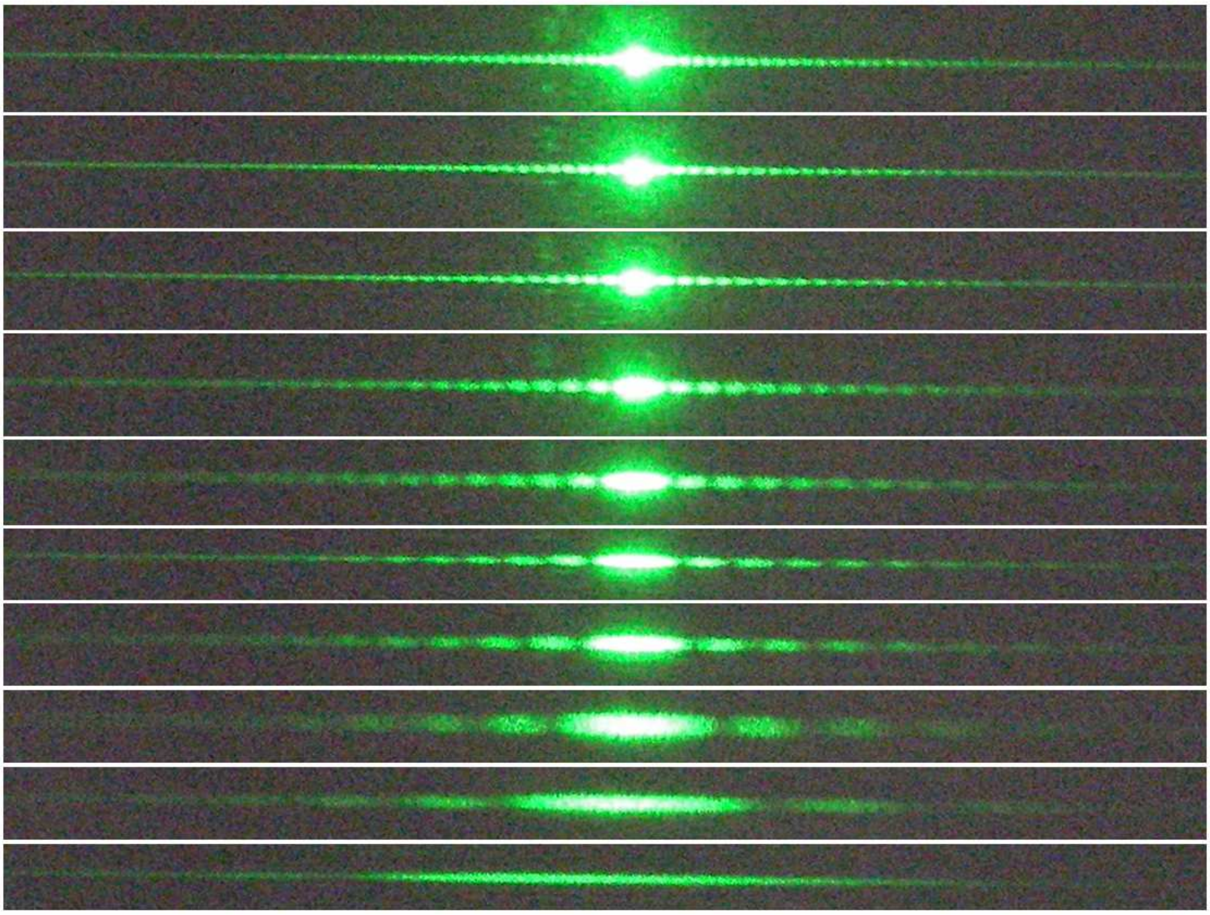


Fig. 21 The images from a single aperture once the additional edge has been moved closer to it.

- Right, it is all clear now! {Shouted Kamila}
- When the edge is close enough to the aperture that hasn't been covered yet, the side fringes are located sideways and blurred to the extent that the detectors don't register them. Now, the brightest central fringe was also blurred, creating the type of light propagation that might be visible in the picture from the book. {The professor noticed}
- So, the image presented in the book is real, and it is fair to suppose that other researchers might have really got the same effect as the one described in the book?
- Indeed, however the drawn conclusions are totally wrong because a single blurred image appearing on the screen doesn't result from the passage of light through a single aperture, but is the effect related to the introduction of the additional edge. Therefore, the described experiment doesn't give us evidence for the existence of the wave-corpuscular duality and the conclusions drawn from it are simply incorrect.
- Is it that based on the experiment that was carried out poorly one drew incorrect and totally absurd conclusions?
- I am afraid that this was the case, Ms Kamila.
- Since we are in the laboratory, I would like to show you one more inconsistency, which I have noticed earlier.
- There is something else? Oh yes, I remember now. When you entered the room you mentioned some new discovery of yours. Please, carry on.
- When I was here the last time, I carried out the experiments that we had done together before. I double-checked the validity of our previous conclusions that light coherence wasn't required in Young's experiment.
Then, I did the basic experiment with the diffraction grating, concluding that the brightness level of

side ‘interference’ fringes barely changes in relation to the fluctuations in distance from the grating (Fig. 22).

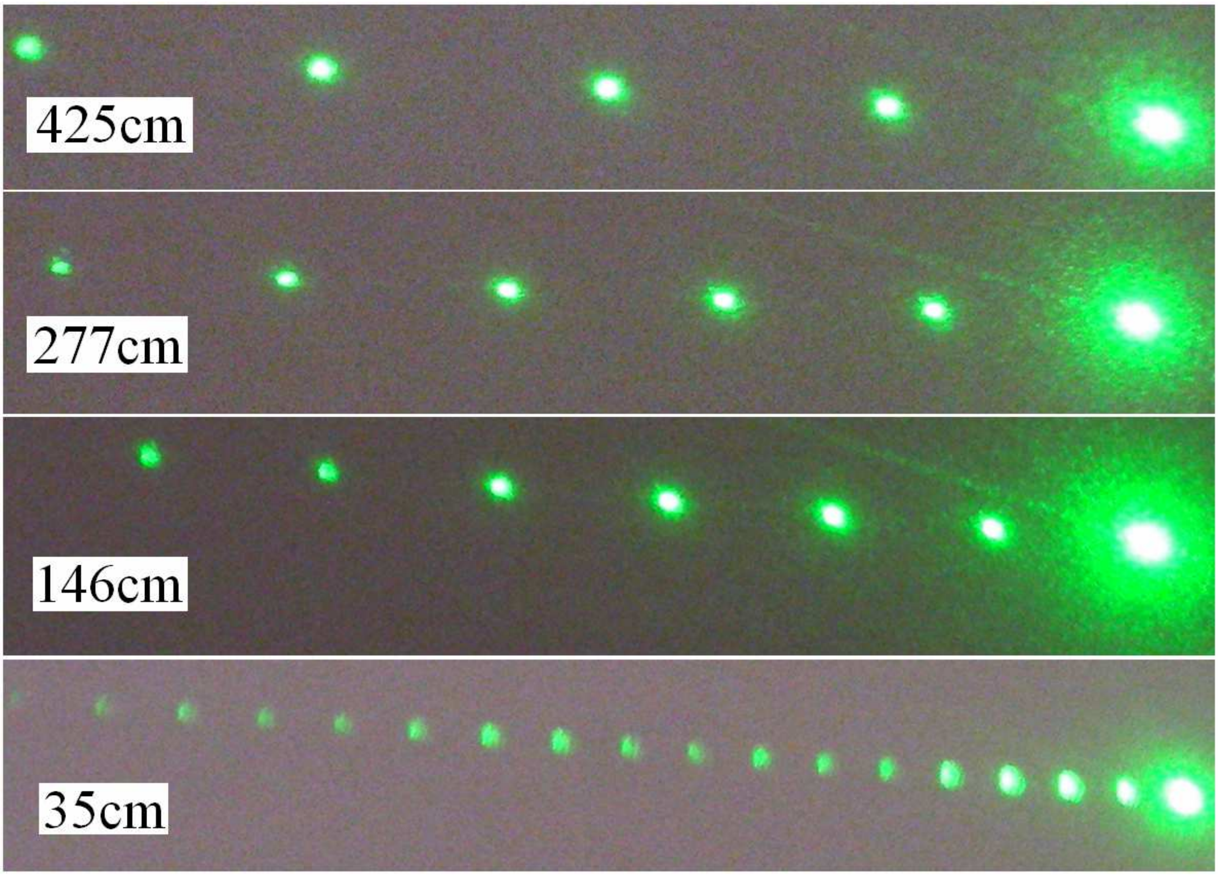


Fig. 22 Images received from Young's experiment with various distances applied from the diffraction grating.

At first I did not observe that, however when I realized that the last seen fringe is at a high angle I assumed that something wasn’t right. In the wave interpretation fringes are interpreted as a constructive interference of waves coming from many apertures. If that is the case, then the waves from each aperture must propagate at a high angle. Is that right?
- Of course.
- Nonetheless, from the mechanics of waves in physical continuum I remember that a propagating wave must visibly (a relatively wide angle of light propagation) diminish its intensity and distance, because its energy is spread across a wider space (surface). Of course, I do not have a precise device to measure the intensity of light. However, I placed my hand near the diffraction grating, at about five centimeters, and next I placed it at a distance of two meters. I didn’t observe any significant changes in the brightness of the spot on my hand, despite such a distance variation.
- Hmm. Let us see how this matter is addressed in our book. According to Mr. Kryszewski's textbook on quantum mechanics, the intensity of each individual side fringe in Young's experiment depends on the distance between the fringe and the apertures. More specifically: “A_i is an x dependent, that is so because the energy of the spherical wave diminishes with the square of the distance from the source (in this case the aperture)”, where A_i is an amplitude of the wave transmitted to the screen from an “i” of the aperture, however “x” is the placed axis on the screen along the “interference” image (Fig.15) [2]. The side fringes lay somewhat further from the apertures and have a smaller light intensity, nonetheless in your description the distance changed almost forty times! Having this distance in mind, it is impossible that the light intensity has not visibly changed for individual fringes, when the light propagates in an arc from the aperture and at a

relatively high angle. Where our assumptions about the propagation of light from the aperture false?

Surprised by this conclusion, the professor placed the diffraction grating on the optical axis and repeated the experiment Kamila referred to. To his even greater surprise, he had to admit that the result was just as she said. The spot of light did indeed enlarge its diameter with the change in distance, however the brightness did not visibly change.
- How is it possible that the brightness of the spot of light does not change? Especially that, according to the mentioned wave description [2], fringes placed closer to the optical axis should rather quickly diminish their intensity even with a very small change in the distance between the screen and the aperture, if of course we would like to explain the loss of intensity by the change in distance (Fig. 23). Have you thought about ways to explain the discrepancy between the theory and the experiment?

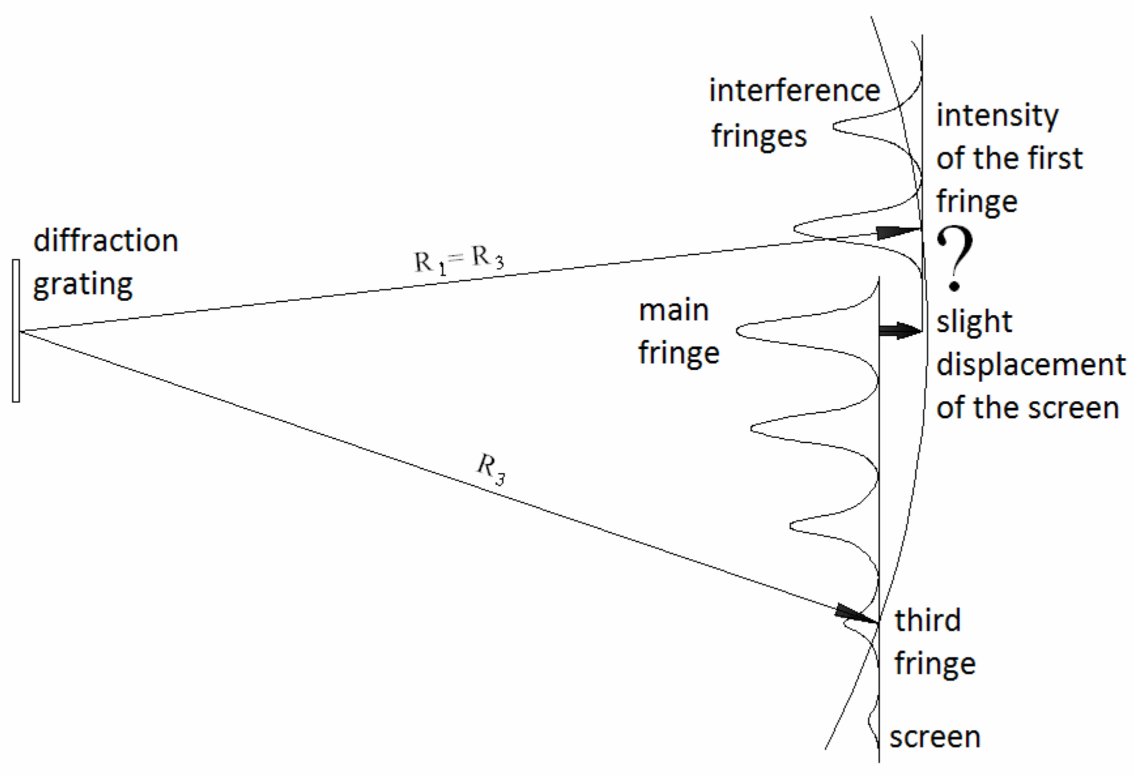


Fig. 23 Diagram showing the change of the intensity in those fringes which are placed closer to the middle of the image with a small displacement in the distance between the screen and the diffraction grating. Diagram detailed in accordance with the wave interpretation shown in the textbook [2].

- Well, I thought about it professor. However, I came to an absurd assumption that the energy would have to be magically transmitted from the destructive interference areas to the constructive ones.
- I am not sure about that Ms, because the screen might as well be placed one kilometer further and what then? The energy is transmitted in the blink of an eye to only a few points? No! This is absurd! There has to be a more rational explanation.
- Yes, indeed, there must be. Later I came to the conclusion that maybe the change in the light's intensity for individual fringes doesn't come from the difference in distances from the apertures, as you quoted from the textbook, because that definitely contradicts the experiment (Fig. 23). Nonetheless, what you quoted from the quantum mechanics textbook is closer to the truth. The intensity of light for each individual fringe (seen as a single fringe on the screen) really decreases with the square of the distance when the distance from the source is measured. Because we assume

that light is a wave, we talk about the changes in the amplitude of the wave and the distance. This assumption is also true for the corpuscular concept, in which the intensity of light is equal to the number of photons per unit of light beam cross section. If the light moved in the form of a cone, the section of the beam would increase with the distance from the source, as well as a number of photons decomposing on a larger area would result in a decrease in the light intensity. Nonetheless, we agreed on the assumption that the number of photons in a section unit does not depend on the angle in which the photons come out of the aperture. There would be no other possibility for this assumption, than to wrongly assume that the decrease in the intensity of individual fringes in Young's experiment depends on the differences between the fringe on the screen and the diffraction grating. It is then more reasonable to assume that the aperture does not react as a source point, contradicting Huygens' law. We may then assume that intensity of the light transmitted from the aperture varies depending on the angle at which the light beam bends from the optical axis. What does Feynman say on this subject?

- I think Feynman's thoughts were similar. Let us look it up in his book. O! Got it! In chapter 29-5 the author dwells upon interference from a mathematical point of view, just as we dwelled upon the instruction for Young's experiment. That is, he assumes sinusoidal wave interference displaced at a certain phase at some point in space. Next, he shows multiple mathematical approaches to the search for the final wave, which is the result of the sinusoidal wave interference [3]. The most interesting one is the geometrical method. In this method the functions: $R_1=A_1\cos(\omega t+\varphi_1)$ and $R_2=A_2\cos(\omega t+\varphi_2)$ can be presented on the coordinate axis (Fig. 24).

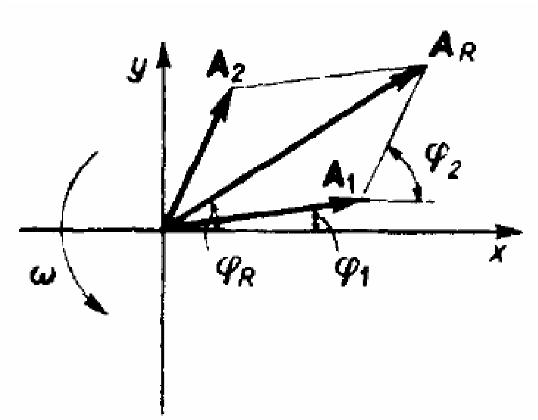


Fig. 24 Geometrical method of combining two cosine waves. One must imagine that the diagram rotates with an angular frequency ω counterclockwise [3].

For this geometrical presentation, functions R_1 and R_2 should be considered as a result of vector projection from the diagram (Fig. 24) to the x axis. In such view, the relative position of the vectors does not change because both rotate with the same angular speed. The final result might be obtained by the adding of both vectors R_1 and R_2, and the projection of the resultant vector to the x axis. This approach is convenient when we take a larger amount of harmonic oscillators into consideration (Fig. 25) [3].

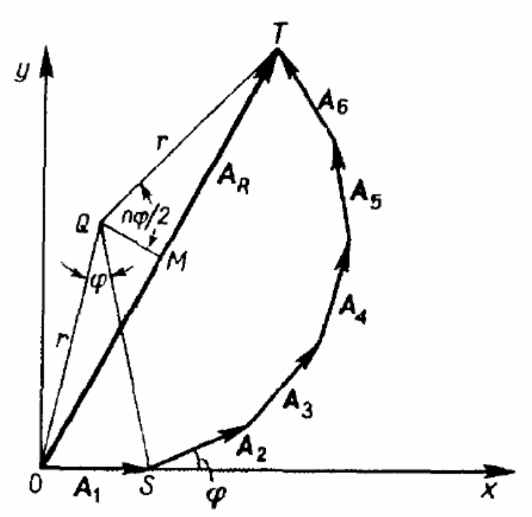


Fig. 25 Resultant amplitude n=6 of equidistant sources, for which the difference between neighboring phases equals φ [3].

- That’s an interesting mathematical approach.
- Indeed, with the use of this method we may gradually discover the true sense of Feynman's thought process. Do you remember when I mentioned that for an individual aperture we may assume that we have an infinite amount of wave sources distant from each other by an infinitesimal distance? We then stumble upon a problem, which is the adding of multiple cosine type functions displaced out of phase to one another. It will be exactly the same as in the diagram (Fig. 25), but with the length A_i of the vector approaching zero, the difference between neighboring sources approaching zero (the sum of all phase displacements does not approach zero) and the number of vectors (harmonic oscillator) approaching infinity. In practice we are talking about such a summation of the vectors for which we imagine a large number of n vectors like in the diagram (Fig. 25). Here we come to the crux of Feynman's diffraction idea. Which is that diffraction and interference are the same phenomenon, but we talk about interference when we come across a small number of light wave sources. However, diffraction is connected with the result of the overlapping of waves from many sources.
- Then, what was Feynman's final result of adding waves coming from different sources but from a single aperture?
- The author doesn’t describe a single aperture, but the situation resulting in the overlapping of many linearly placed harmonic oscillators. Before I present Feynman's final result I would like us to look closer onto the diagram (Fig.25).
- The quantity A_R of the vector placed on an arc and outlined by A_i vectors, depends on the displacement of phase φ, which then depends on the angle from which we observe our linearly placed oscillators. The full angle at which the last vector A_n will rotate is nφ. This is the phase displacement for the last oscillator. The full rotation is 2π. Then the measure of the direction in which our observation continues is nφ/2π. Also the intensity of the resultant wave can be presented as a quantity referred to the overall value of intensity which is the sum of all oscillators' intensities without phase displacement. This way Feynman received a relationship for wave intensity coming out of a single aperture (diffraction) in the function of the direction of wave propagation (Fig. 26).

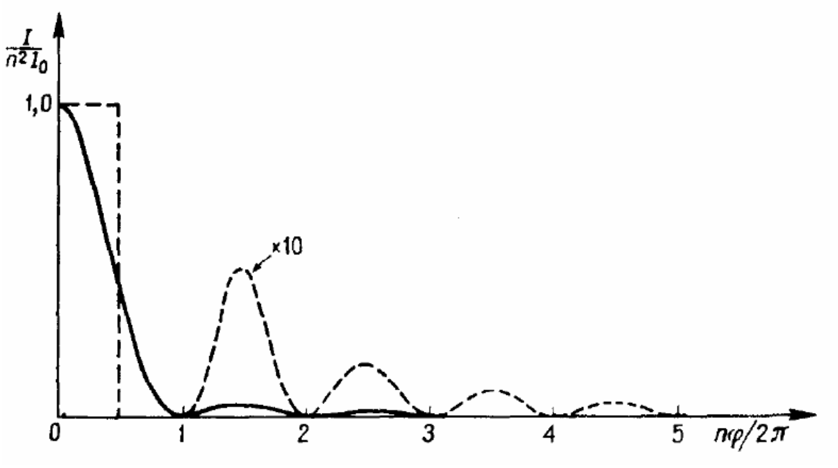


Fig. 26 Intensity as a phase angle function for a large number of oscillators with an equal intensity [3].

- This is remarkable, he was able to achieve two things at one go. That is the appearance of fringes for a single aperture and variable light intensity for individual fringes. However, you still didn't clarify how Feynman determined individual maxims.
- Well, this is not so hard Ms Kamila. Please look at the diagram (Fig.25). If we assume that all A_i vectors are equal, we may accept that the n of such vectors outlines part of a circle. Then it is easy for us to deduce a relationship for the vector quantity A_R. We simply use the QOS triangle to determine the r length, next we use the QMT triangle to determine half of the A_R length. Thus:

$$A_R = A\frac{\sin(n\phi/2)}{\sin(\phi/2)} \quad \text{and} \tag{4}$$

$$I = I_o\frac{\sin^2(n\phi/2)}{\sin^2(\phi/2)} \tag{5}$$

- Now I understand! For various fringes we have a different φ phase displacement. Because sin(φ/2) changes slower than sin(nφ/2) for a high n value. For another φ, where $\sin^2(n\varphi/2)=1$, the denominator sin(φ/2) only changed slightly. That is why the next amplitude will be approximately $\varphi=3\pi/n$. When we substitute the denominator with this angle we will receive $\sin^2(3\pi/2n)$. For a high n value it is a sine of a very small angle. That is why we can substitute the denominator with $(3\pi/2n)^2$. Then the intensity in approximation will be $I=I_0(4n^2/9\pi^2)$, because $I_{max}=n^2I$, the next peak on the diagram (Fig. 26) will approximately be $4/9\pi^2$, that is 0,047. The next fringes will be even smaller [3].
- So you see, Feynman correctly described light's reactions to a single aperture. He did not only describe the appearance of fringes, but also the decrease in amplitude.
- Indeed, it seems he explained the problem very well. However, is the decrease in amplitude for individual fringes exactly as Feynman foretold, that I don't know. Nonetheless, let us pay attention to another important matter. Young was also correct in assuming where the fringes would be placed. Sadly his assumptions require reasoning which cannot be deemed to be correct in the light of preview experiments (light coherence). What type of reasoning did Feynman apply in his assumptions? Let us look at this closely.
- Right, let us do that: [3]
Thus we shall now discuss the situation where there are n equally spaced oscillators, all of equal amplitude but different from one another in phase, either because they are driven differently in phase, or because we are looking at them at an angle such that there is a difference in time delay. For one reason or another, we have to add something like this:

$R=A[\cos\omega t+\cos(\omega t+\phi)+\cos(\omega t+2\phi)+\cdots+\cos(\omega t+(n-1)\phi)]$,(30.1)

where ϕ is the phase difference between one oscillator and the next one, as seen in a particular direction. Specifically, $\phi=\alpha+2\pi d\sin\theta/\lambda$. Now we must add all the terms together. We shall do this geometrically. The first one is of length A, and it has zero phase. The next is also of length A and it has a phase equal to ϕ. The next one is again of length A and it has a phase equal to 2ϕ, and so on.

- That is what I feared. You see professor, Feynman assumed that outgoing phases must be well defined at the beginning. He also assumed that we are dealing with the source of a coherent wave, both in time and space. This means that Feynman correctly conducted diffraction with a single aperture, but it was only possible in very good initial conditions, that is a coherent wave source. His explanations would be completely worthless if he was conducting a real experiment where there was room for incoherent light. That is why he truly didn't explain anything.

- Indeed. This may cause a serious problem. Every researcher referring to your experiments with fringes regarding incoherent light, will be able to discard the assumptions of Feynman and Young, as well as others thinking along the same lines.

- Finally, I think that this whole phenomenon takes place in the area of the aperture and only there. There is something interesting in that area that divides the light beam into a few individual beams under different angles. The divided light travels free from interference until it reaches the screen, a detector or any other object. Then it does not matter where one places the screen, because always the same amount of photons that are transmitted through the aperture under a certain angle will be displayed. However, the intensity of individual fringes depends solely on how many photons will be shifted in the aperture or the edge in a certain direction.

Kamila, not knowing what to think on the matter of light, started to pace up and down the laboratory. She was trying to think of an explanation for the division of light in the apertures. Deep down, she knew there was a rational explanation. Strolling along a different laboratory station, she took an optical lens and returned to the professor.

- Maybe we should see what will happen with the light when we transmit it through an optical lens?

- Nothing of significance. {The professor replied} The light will simply be focused in one place from which it will travel onwards creating a big spot on the wall.

Kamila turned on the laser and placed the optical lens. Instead of a spot of light there was a big rectangle on the screen (Fig. 27).

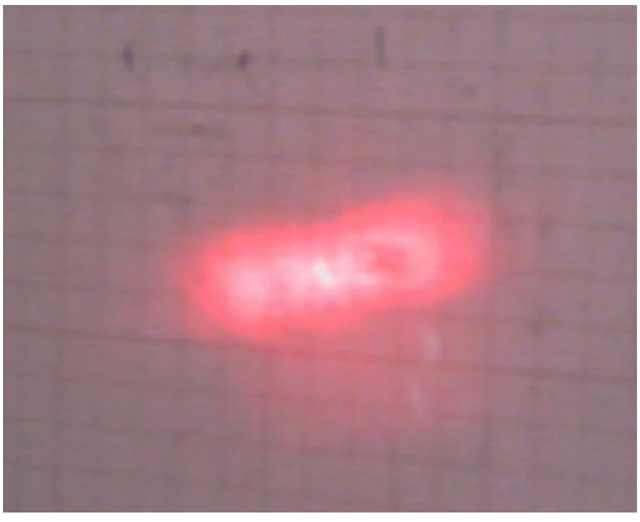


Fig. 27 Depiction of a laser light beam propagated through an optical lens.

- I thought we will receive a big round spot on the screen. Why does the shape resemble a rectangle?
-Because this light comes from a laser diode. Its shape in rectangular and the light comes from the side which has that kind of shape.
- I understand. So the shape of the light beam on the entire length must have the same shape. However, the lens after the propagation shows the shape of that beam, that is a rectangle.
- That's right. Since we are playing with the lens, let us see what will happen when we add a diffraction grating.

Kamila took the diffraction grating into her hand and placed it closely behind the lens. They saw a duplicated image of the light beam cross section that differed from the original only in brightness (Fig.28).

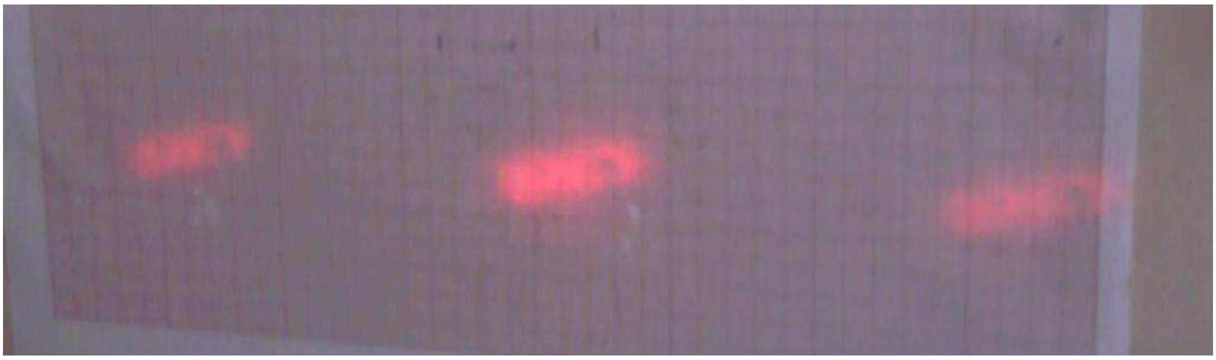


Fig. 28 Image depicting a laser beam propagated through an optical lens and diffraction grating.

- Well, the image multiplied. {Kamila said in a humorous manner} Also the brightness of the lateral images is lower like in the original experiment. It's very interesting that we have similarly shaped images to the original.
- Why would they be different?
- I don't know. How can this experiment be different from the original? Maybe it depends on the number of apertures the light is transmitted through? Of course, the number of apertures through which the light is transmitted is equal to the light beam cross section divided by the grating constant. When we have a beam cross section as seen on the screen, it means that in different parts of the diffraction grating light is transmitted through a various number of apertures. Does the image on the screen depend on the number of apertures through which light is transmitted?
- Yes. The more apertures the light is transmitted through, the thinner the fringes on the screen are and vice versa.
- I understand that this refers to wave interpretation in this experiment?
- Of course, why do you ask?
- Because something is not right about this image. If the width of the image depends on the number of apertures included in calculations, as stated in contemporary theories, then it is impossible to obtain the exact same shape of the image after it passes through the diffraction grating. However, we saw the same without the grating!
- Hmm. In fact if it were as I said, the middle of the light beam transmitted through a lot of apertures would result in a very thin image. However, at the top and bottom of the light cross section the number of apertures lessens and the image should grow wider.
- But this doesn't happen. Additionally, we have a hole in the middle of the image presumably as a result of the lens in the laser being dirty, it doesn't change its place or shape but has an impact on the number of apertures through which the light beam is transmitted at the center of the image.
- Exactly.

- So, once again the assumptions of wave theory contradict the actual experiment.
- Seems like it. This morning when I did a simulation I was certain that everything was intact, I see now that I was wrong.
- If the use of the lens and diffraction grating causes new inconsistencies within the theory, then maybe we should try to use a monitor grating?
- That's a very good idea.

After the removal of the diffraction grating, Kamila placed the monitor grating in the same place, that is behind the lens. The image they saw was of the same size but, also, it was made out of many points (Fig. 29).

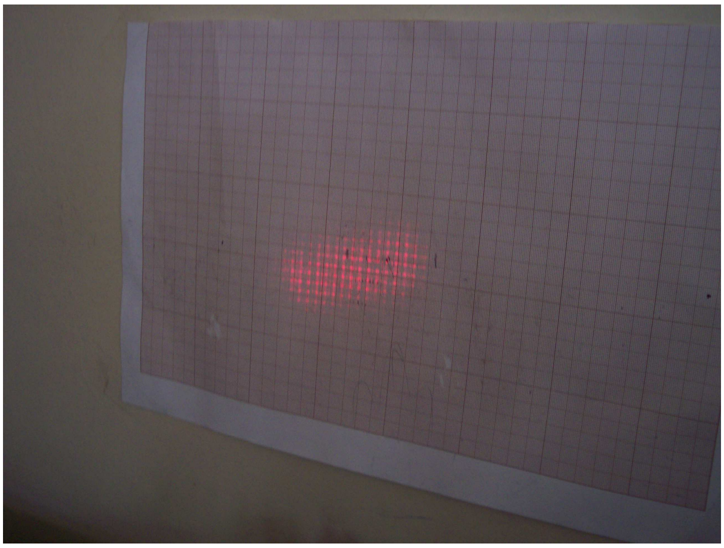


Fig. 29 Image on the screen obtained from the transmission of a beam through an optical lens and monitor grating.

- Excellent! Something new. {Kamila cried out}
- I have not seen this before. Let us consider what we see before us. The shape and size of the envelope stayed unchanged to that obtained without the grating (Fig. 27). What may the points on the screen indicate?
- I think that maybe the apertures in the grating. The grating is nothing more than crisscrossed perpendicular fibers. Light may be transmitted between the fibers and that is probably what we are observing right now.
- But how can we be certain? Can you please move the grating back and forth?
- Yes, of course.

When Kamila moved the grating the number of points seen changed, however there was a place for which the number was the smallest. Additionally, by increasing and decreasing the distance between the lens and grating, the number of points grew. The spotted image, however, still had a rectangular shape, which was connected with the shape of the laser beam cross section.
- I know! {cried Kamila} When we have the smallest number of points, the grating is placed at the focal length of the lens. By moving the grating closer and further from the lens, we enlarge the area through which the light is transmitted. Thus, we can observe changes in the number of points on the screen.
- It is possible that you are right. Let us confirm this by rotating the grating. If the points on the screen are truly the reflection of the grating's apertures, then by rotating it at a vertical axis the number of points on the screen will increase in a horizontal direction and the width of the spots of light in this direction will decrease (Fig. 30).

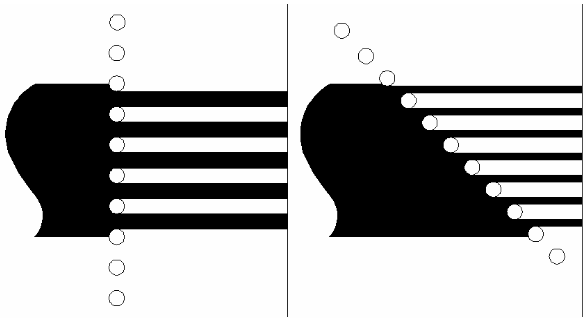


Fig. 30 Diagram depicting changes in light propagation during the rotation of a grating in one axis.

Kamila rotated the grating as the professor asked. The image on the screen changed in line with the expectations voiced.

- You were right. The image truly represents the apertures of the grating in enlargement.
- Let us see what happens when we place the lens on the other side.

Kamila repositioned the grating so it was placed right in front of the lens (between the source of the laser light and the lens). Then, the laser light was transmitted through the grating first and then through the lens (Fig. 31).

Fig. 31 Laboratory table with a laser, monitor grating and lens placed behind the grating.

Initially, the image on the screen did not differ from the previous one. The rotation of the grating also resulted in the rotation of points on the screen, and the rotation in a vertical axis changed the number of points seen in the horizontal direction as before. A difference occurred only after Kamila started to change the distance between the lens and the grating. No matter how far the lens was placed from the grating, they always saw the same amount of points on the screen.

- Interesting! {Kamila said surprised and, after a while, added} The number of points on the screen doesn't change, in spite of the distance being subject to change. But this may be easily explained. As we concluded before, the number of points depends on the amount of apertures through which light is transmitted, this means that this time the number of apertures in the grating lit by the laser didn't change substantially.
- Of course! This time the light is transmitted through the grating first and has a specified cross section. Because the light of the laser travels almost in parallel, in case of a slight displacement of

the grating on the optical axis, the area of the grating lit by the laser almost does not change at all. Behind the grating the light is already divided into individual beams transmitted from each aperture and thereafter deflected by the lens. That’s why, we can see the cross section the light beam creates behind the grating in an enlargement.

- Great, but where are the 'interference' fringes? {Kamila asked}

The professor relocated the grating to the other side of the lens and placed it in such a way so that one saw the smallest number of apertures.

- They are here. {He continued} Each brighter spot reflects an aperture of the grating as we noticed before. If we take a closer look, and in this position one may see most clearly (grating in the focal length of the lens), each aperture of the grating has its own interference image.

- Yes, I see now. At the previous placement of the instruments (the grating placed between the source of light and the lens) one could also see additional fringes (Fig. 32). Maybe if we moved the lens further in the direction of the screen, it will be more visible (Rys. 33.).

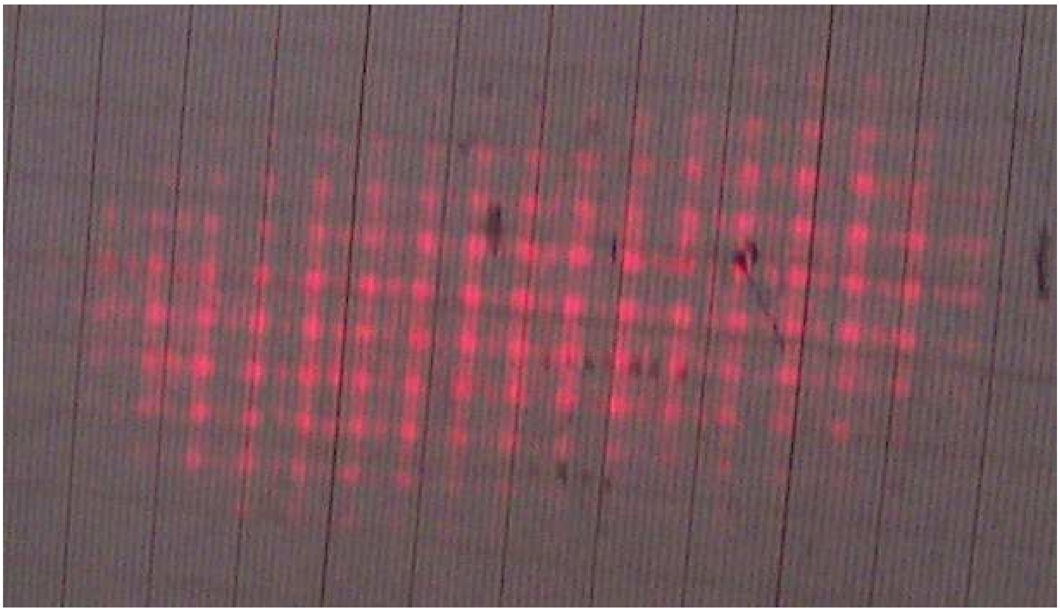


Fig. 32 Image on the screen created from the transmission of the beam through the grating and lens. Brighter points define the placing of the grating's apertures. Less brighter points on both sides are 'interference' fringes.

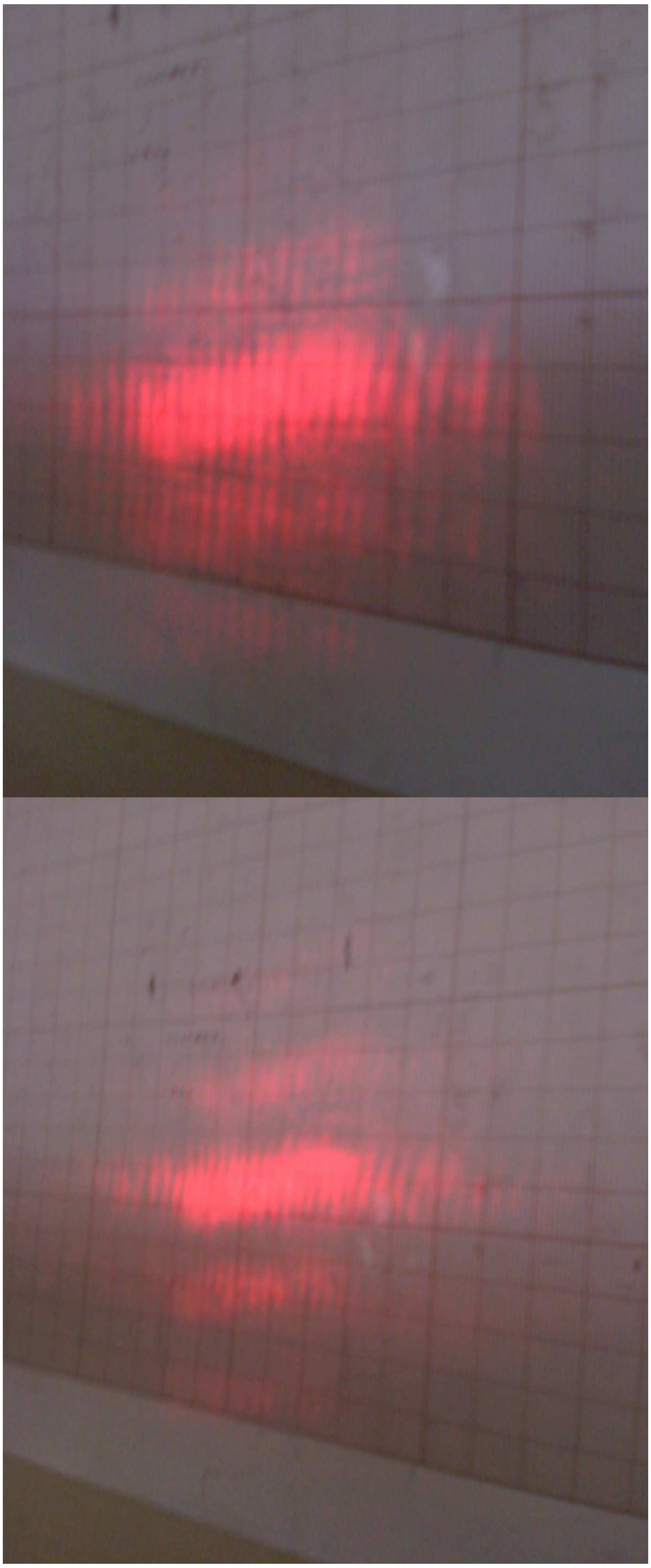


Fig. 33 Image on the screen created by the transmission of a laser beam through a grating and propagating lens placed at some distance from the grating. On the right, one may see a wider displacement of the lateral fringes as a result in the increase of distance between the lens and the grating.

While moving the lens away from the grating, the image began to divide into separate fields depicting the rest of the fringes. At a significant distance, the image resembled that from the original experiment (without the use of a lens, Fig. 3). However, before the image from the fringes merged into one, one could observe that it was also made out of points, which simply corresponded to the grating's apertures. This surprised both Kamila and the professor.
- Now I see where our fringes hid. {Kamila said in a humorous way}
- Yes, but the interesting part is that they are also made of points corresponding to the apertures in the grating and create a rectangular shape from the light beam transmitted through the grating, just as the main image did.
- I think this can only be explained in such a way: a few light beams must be individually transmitted from each aperture, and those transmitted at a certain angle travel in a parallel manner (Fig. 34). {Kamila added with pride, knowing that this is a complete contradiction to wave interpretation}

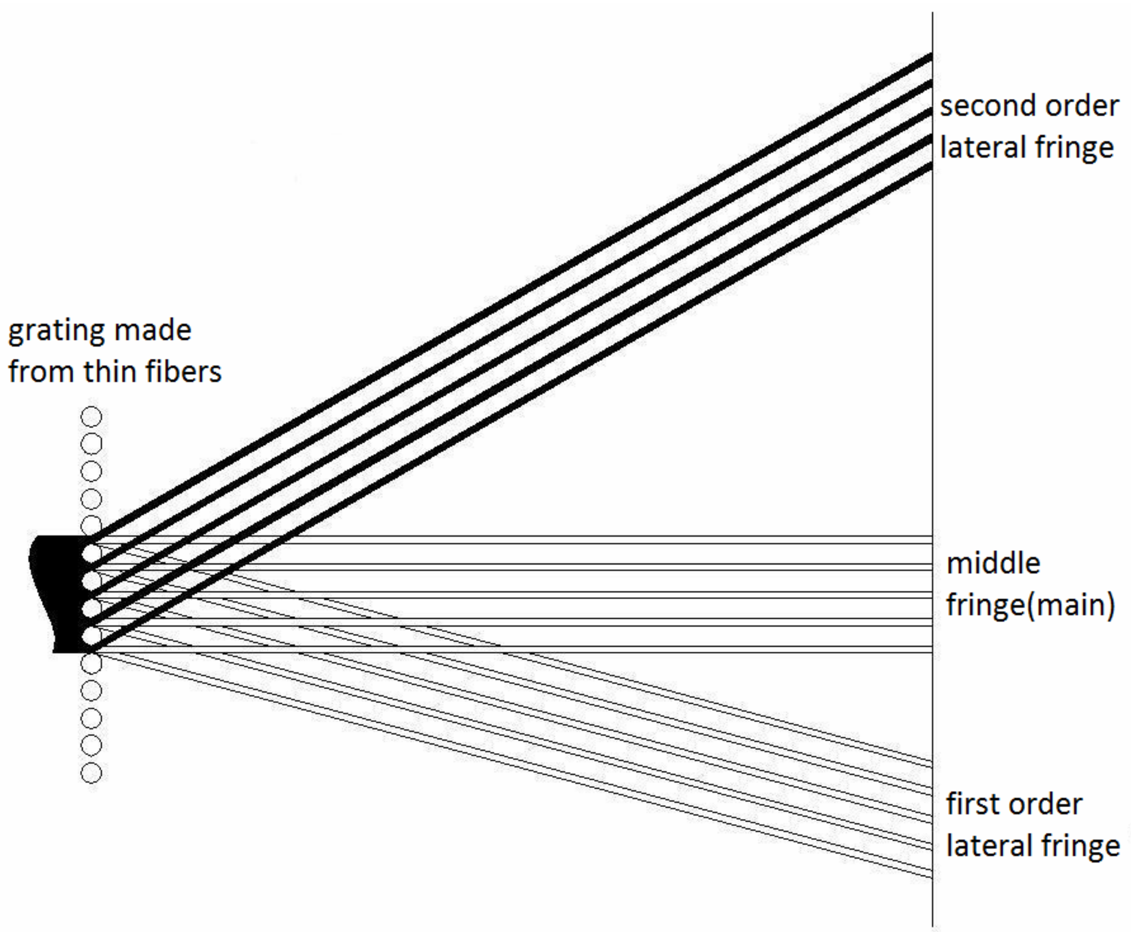


Fig. 34 Schematic depiction of the mechanics of lateral fringe image creation consisting of light points corresponding to the grating's apertures and the shape of the light beam transmitted through the grating.

- This requires an assumption in which light is discretely propagated at certain angles in each aperture (edge) independently for each photon! {If the interaction of the edge on the light has a wider range than the distances between apertures, then one must expect that the deflection of light in every aperture won't be totally independent. The experiment with a single aperture and diaphragm (Fig. 21) showed that such an interaction is quite significant in relation to the length of the light wave. This may be observed when one conducts the mentioned experiment}
- That's right. However, such an assumption explains why the image depicts the apertures of the grating. The lens only enlarges the beam's cross section image, which already exists behind the

grating. That’s why, we can see how it really looks like, and not only individual diffused spots. This also explains why the shape of individual fringes was the same for the diffraction grating and the main beam (Fig. 28).
- Yes, well, wave theory is not successful in producing the right shape of the lateral fringes in this experiment.
- Also, with this, one may explain another inconsistency in wave interpretation.
- Which is?
- The behavior of the brightness of lateral fringes, which doesn’t differ with the change in distance from the diffraction grating. For such an interpretation, it doesn’t matter where the screen is placed. We should still be able to obtain a fringe with an unchanged brightness.
- It is hard to agree with this, especially when we assume that the light deflected in the apertures travels free in a straight line from interference. However, the existence of fringes would depend solely on what would happen to them in the area of the apertures.
- Choosing this assumption, explaining the following is not a problem anymore: Why is the fringe image created for a single aperture or edge? One does not have to contrive what interferes with what and create absurd conceptions.
- But Ms Kamila, what is wrong with an image created from a single aperture?
- I will tell you what is wrong: the image of the fringes is symmetrical and is also created on the shadow side. Even more, the fringes are placed wider than the width of the light beam which is transmitted onto the edge. What do you think interferes there? The answer is that nothing has to interfere there at all. One must only find the cause of light's (or particle) discrete division into a few beams and the problem is solved.
- Well it seems like it, but for many physicists this will be quite hard to digest. However, in the light of our recent experiments, there is no doubt that we must rethink this idea. Maybe we should find other experiments which will enable us to find the solution. Aha! Please, note that there is one more consequence of this explanation of the observed effects which is derived from your drawing (Fig. 34). If the lateral fringes are made out of points that represent apertures in the grating (what the experiment shows!), it is obvious that the light from each aperture must travel in a parallel manner. However, then the light from each aperture theoretically never meets on the screen!
- So, this completely dismisses the idea of interference in this experiment.
- Anyway, the concept referring to the propagation of the beam into many others, on each edge independently, is coherent with the concept explaining the appearance of a fringed image on the grating (Fig.11).
- So, we are getting a more clear and coherent image of the processes occurring in Young's experiment. The photons are discretely propagated on each edge. If we have many identical edges placed closely to each other (equal conditions for photon propagation), then there will be enough deflected photons in some directions to observe on the screen as an individual fringe.
Such an explanation does not require a light coherence theory, because in each aperture the photons are propagated independently. Then, the cause of the observed phenomenon has its source in the area of the aperture, not on the screen and the “light wave” coherence is irrelevant. We must also research if the photon behavior in the area of the aperture depends on: geometrical shape of the aperture (not only the distance between apertures), the material from which the aperture is made and the temperature of the aperture.
- A very clever remark Ms Kamila, but we must find a more detailed description of the occurrences in the area of the aperture and explain why light behaves in such a way. Additionally, it is very interesting to see at what point does the closeness of apertures relate to the propagation of individual photons. The behavior of each aperture is not necessarily so independent, but this requires a closer study. I wonder if we should first carry out a simulation based on wave interpretation or try to obtain an image reflecting the placing of individual apertures of the grating, as presented in the experiment (Fig.33).
- I think it is a good idea, but I have my doubts professor whether we will not stumble upon the same problems as we did with Feynman's assumptions? I mean, wave interpretations are based on

interference, as we concluded before, and are sensitive to initial conditions. More specifically, the differences in phases resulting from the difference in the paths of individual light beams. Such an approach needs a very good definition of the initial conditions, that is making an assumption regarding the coherence of light used in the experiment. We already proved in earlier experiments that the phenomenon also occurs for incoherent light. If not for this limitation, I could easily say that Feynman already showed that there are fringes for a single aperture. If I assume that every aperture behaves completely independently, then analyzing each aperture in turn we will have the same situation as seen in the drawing (Fig.34). With only one reservation, that in the analysis of a single aperture as an independent creation from other apertures, we should obtain the placement of fringes dependent on the size of the aperture and not the distance between apertures. Meanwhile, the comparison of the size of the grating, calculated on the basis of the placement of fringes on the screen and the removal of the grating under microscope (Fig. 6 and Table 1) showed, that the result is closer to the distance between aperture not between edges.

If we discard the assumption of light coherence, you will always have a problem in defining the true initial conditions for your simulation. With that said, I assume as sensible such initial conditions, where the phase is accidental and changes in time for individual light beams come into the simulated system for each aperture independently. I fear, professor, that nothing sensible will come out of a simulation based on the interference of different waves.

- Sadly, you are right. As always everything comes down to the basic assumption of light coherence. I think this will be all for today. It is getting late, time to go. If you come up with more interesting remarks on the subject, please let me know.

- Of course professor. {Said Kamila proudly and left}

For many days, the professor found himself to be notoriously tired. There were so many thoughts in his head that resulted in the development of insomnia. He had to sort everything out in his head. His widespread knowledge, however, did not make it easier for him. On the contrary, it was harder for him to accept that so many matters, till now obvious to him, would need to be verified in light of recent experiments. Suddenly, he had an idea to consider a thought experiment, which would consist in the closing of a source of light in a box with only a small hole. The light would then travel through that hole as a thin beam. Then he asked himself a question: What can be said about this light and what kind experiments would be necessary? The first thing that came to his mind referred to the color of light. To establish that, one needs a piece of white paper which would cut the light beam and result in the showing of the color of the spot of light.

- Is that really so? {He thought} - Of course, it is not. Even Newton already observed that light can have many colors (seen), it depends on the mixture of colors it is made of. One must do what an English scholar did ages ago. That is to cut the light beam with a prism. Because light composed of various colors refracts on glass, it will then separate into all the colors it is made of. The contemporary name of this phenomenon is spectral resolution and it allows to establish the length of light waves from the researched source. One may also use a diffraction grating.

Is there more to determine for such a hypothetical light beam? Of course, light can also be polarized. To do this, one must take a polarizer into one's hand and place it on the optical axis. {Pure simplicity - he thought} Next, one needs to point the light to the wall and by rotating the polarizer check if the brightness of the spot changes. If it turns out that only some colors are polarized, then not only would the brightness change but also the color. So, the polarization of individual colors of the light beam is such a property, which can be also easily established by an experiment. In a more complex pattern of individual color polarization, one may also use a prism and then check each color with a polarizer.

As for now, he did not find any difficulties in describing such qualities as color pattern and their polarization. What other quality may a light beam have? Of course, it can also be coherent or incoherent. The obvious choice is coherent light, when one uses a laser as the source of light, but in his experiment he did not know anything about the type o light he considered. He then wondered: What kind of experiment must one use to establish if the light is coherent or incoherent? The first thing that came to his mind was Young's experiment. It is clearly stated in the laboratory instruction for this experiment that it is a necessary condition to conduct the experiment. Unfortunately not! He clearly remembered the “interference” images he saw for incoherent light. So, irrespective of the reason for the creation of such images, the mentioned experiment may not be conducted to verify the light beam coherence. What other experiments would be suitable to verify this quality? {Wondered the professor}

Looking for the answer to his own question, he came up with an additional question. In what experiments is light coherence important? He quickly assumed that the kind of experiments which directly relate to interference. The results are obtained in the same manner as in Young's experiment. He decided to think about a few of them and check if they are suitable to verify the coherence of light. He started with Newton rings and colors created on thin layers. That was not a good choice. He quickly remembered that one may use sunlight for both experiments, which is definitely not coherent. Colors on thin layers were seen by anyone who ever saw a thin layer of oil spilled on the concrete or puddle. Colorful soap bubbles are also interpreted as light interference on thin layers, and almost everyone enjoyed them as a child in incoherent daylight. (I will leave it to the reader to prove that regarding recent experiments, and in light of accepted interpretations, light coherence is essential. The fact that is not often discussed! This is a result of the “interference” between the light reflected by the top surface and that coming from a different part of the light beam section, which was reflected from the bottom surface of a thin layer. Therefore, the whole section of the beam should have the same phase - coherent light!).

He also did not do well with Newton rings, because he himself remembered showing colorful concentric circles, which are created when daylight is transmitted through a lens with a high angle of curvature, during his lectures. At the end he thought about another idea with the use of an interferometer. At first, he was very happy when he remembered that the workings of an interferometer are based on the overlapping of two coherent waves, which results in the creation of quenching areas and the intensification of vibrations. However, after a while, he also reminded himself, that this would be a dead end, because a man named Michelson, whom he mentioned to Kamila earlier, invented and built his own interferometer about a hundred years ago. That was a very long while before anyone invented a laser, which also meant that Michelson must have worked on incoherent light.

The professor began to doubt if he were able to find any experiment, which would be suitable to verify the coherence of light. Then, he remembered Kamila's words:“[t]he interpretation of this occurrence nowadays is in fact purely geometrical and is based on the calculation of the differences in distance so as to explain the appearance of constructive (strengthening) or destructive (weakening) interference”. And what is more, for such an interpretation there will always be the need to establish initial conditions (initial light wave). In practice, there is a need for the assumption that the light used in the experiment must be coherent: both spatially and in time, or one or the other. In that moment, the professor understood that in practice, in every phenomenon related to the interference of light or wave of matter, revealing that it also occurs for incoherent light can discard wave interpretation. Because he was at a loss in finding an experiment which would in fact (in practice) need such an assumption, he felt very disappointed. Am I not able to prove in an experiment: Is the light given coherent or incoherent? If so, then the concept of coherence is totally useless, only theoretical and impossible to verify by an experiment. Maybe the notion of coherent light does not exist at all, if I cannot verify it by experiment!

After coming to such conclusions, he decided to look closer at the workings of a laser, as it is commonly known to be the source of coherent light. The heart of every laser is an active medium, which enables the strengthening of light intensity due to its excitation. In short, there is an assumption which states that in such a medium there are places (crystal lattice additives, or CO_2 particles in a gas laser), which are able to capture part of the external energy (go into an excited state), and release this energy in the form of an emitted photon. The energy needed to excite such places comes from a light that has more energy, an electrical discharge or other phenomena (like chemical reactions) (Fig. 35).

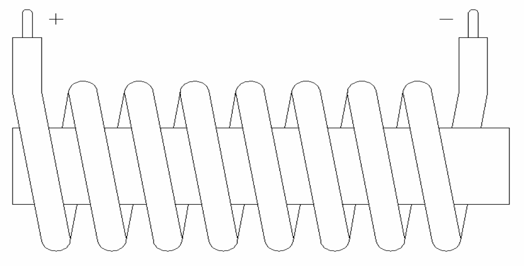


Fig. 35 The laser core based on a solid body with a wound ultraviolet lamp.

In order for light to be emitted, the laser core must be additionally intensively cooled. Then, one may observe the so-called population inversion, which, based on the understanding of occurrences taking place in the process, leads to the radial release of energy in the form of light of certain colour – illumination (Fig. 36). Otherwise, the medium just gets warmer.

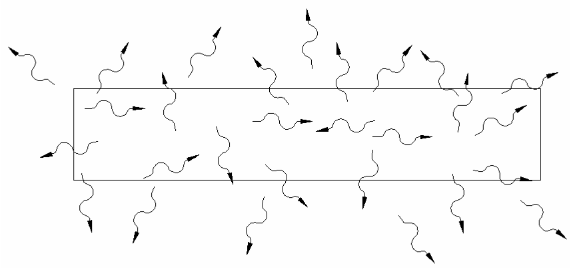


Fig. 36 Radial release of energy accumulated in the laser core.

In such a way, one will not obtain a laser beam but only a shining glow of the crystal, which may be easily compared to the operation of a lamp with filter (one color) or the phenomenon of luminescence. After a while, excited atoms will release their energy, however in a random direction and phase. In order to create a laser beam, one must insert two mirrors into the system, including one that is semi-transparent (Fig. 37).

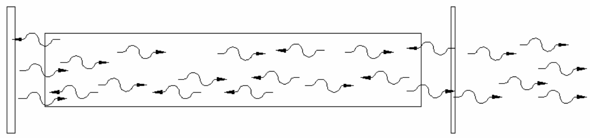


Fig. The laser core surrounded by two mirrors which allow the release of radiant energy in one direction.

Under such circumstances, the excited medium will readily release its energy ahead of time on condition that the photon that falls onto it would bear the same energy as the one that would have been generated. It is assumed that the additionally emitted photon has the same energy and direction as the one which initiated its emission. Because the mirrors are placed in such a way as to allow the photons travelling in one direction to turn back and re-enter the space of the laser core, they also induce other photons, whose direction is determined by the mirrors, and which becomes the dominant direction of light emission. After a short while, the intensity of light travelling perpendicularly to the mirrors grows to such an extent that light emitted in other directions is considered negligible.

It is this assumption, whereby the emitted photon has the direction and phase of the incident photon, that serves as the main argument to treat laser light as coherent. But is it really the case? {The professor pondered over the subject for a while} And what if atoms emit light of the same energy (color) and direction as the photon initiating illumination, however at different times? What if there is a slight delay? Then, the assumption that light is coherent is unfounded. However, being in possession of no valid arguments that that could be the case, he assumed that the official interpretation was correct and set out to search for other possible inaccuracies.

At some point, he realized that every laser generates incoherent light during the start-up phase. After all, the first stage consists in inducing the active medium which initially emits light in random directions and different places of the laser core independently (incoherently). Only by strengthening the photons which were emitted perpendicularly to the mirrors, one is able to strengthen the course of light in the desired direction and witness the disappearance of emission in the opposing direction. However, it so happens that at the initial stage many photons could have been emitted separately towards the mirrors and, coming from different parts of the core, could have created a common initial beam. There is no reason to believe that any one of the photons is better than the rest. They are equal and in theory each of them can be further duplicated. It would mean that the final beam leaving the laser would be comprised of a large number of duplicated original photons with no past or present coherence in between them. Finally, it is safe to say that there is no theoretical claim to assume that the laser beam is coherent. Since it was not coherent from the outset, it will still remain so despite having been strengthened. That is because multiple incoherent beams that are strengthened in a coherent manner would still create an incoherent beam. The result of theoretical deliberations did not worry the professor too much, since he had already established the there was not a single experiment which would enable him to scrutinize the coherence of any examined beam of light. In that case, his conclusions were purely academic and had no bearing on further deliberations.

Next day, the professor ran into Kamila in the hallway leading to the auditorium.

- Good morning professor! {Shouted Kamila clearly excited about the encounter}
- Good morning, did you get a good night’s sleep? You look exhausted.
- I am, indeed. I spent the whole night on the internet searching for new materials related to light and interference. I was wondering what other interesting experiments can be carried out.
- Did you find anything interesting?
- I guess so. I was browsing through data related to interferometers and I found out that they require coherent light. Can we examine the necessity of applying coherent light in this experiment?
- There is no need for that, Ms Kamila. I also worked a lot last night and I managed to find out that, in the case of interferometers, light coherence is not required.
- I expected that, however I really wanted to check something else.
- And what would that be?

Kamila took out her notebook and drew a small diagram portraying Michelson’s interferometer. It consisted of a laser as the source of light waves (wave interpretation), two mirrors, including a mobile one, as well as a semi-transparent diaphragm (Fig. 38).

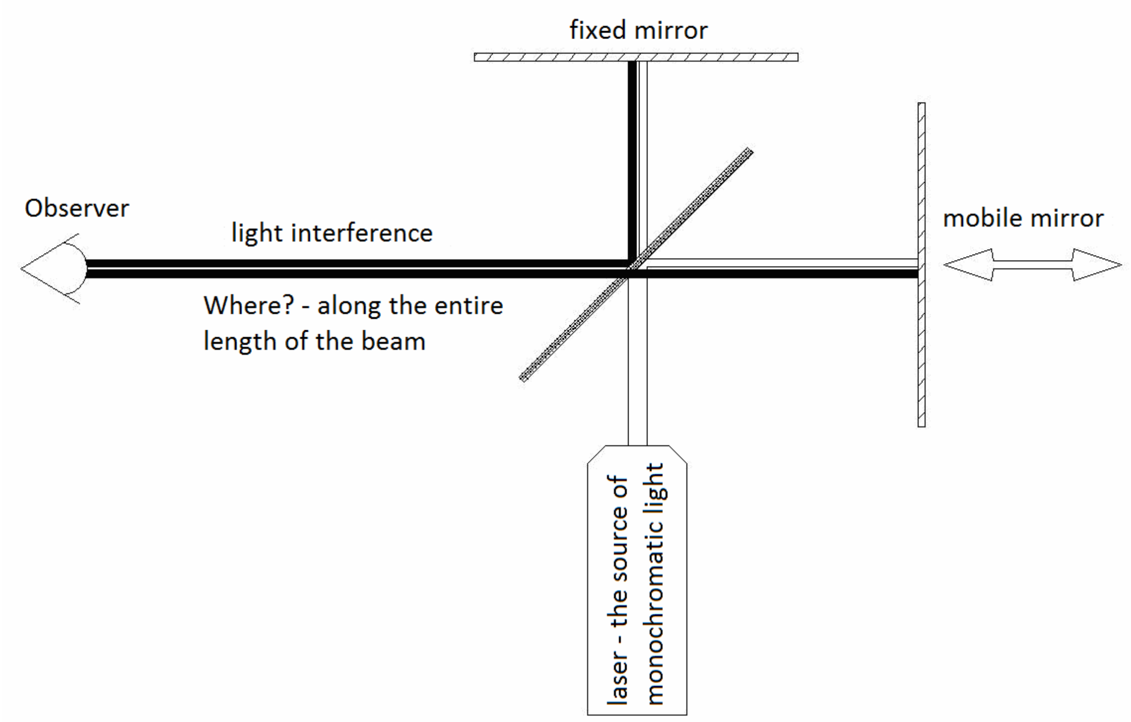


Fig. 38 The diagram of Michelson's interferometer. Light passes through a semi-transparent surface, where it is divided into two beams of equal intensity. Then, after being reflected by the mirrors and having been combined again, those return to interfere with each other.

- As we know {She continued}, the semi-transparent diaphragm is supposed to divide the light beam into two beams of equal wave amplitude. Then, the separated beams follow different optical paths and, having been combined again, interfere with each other. Depending on the phase shift between the beams that are combined again, the observer may, or may not, see the light. If the relative phase does not change, then we will have to do with constructive interference and the observer will be able to see a spot. If the phase shift between the beams takes place out of phase, then the beams cancel themselves out and the observer doesn't see any light.
- In order for that to make sense, light must be coherent.
- Of course. At the moment, I assume that the wave interpretation is correct.
- I understand, please carry on.
- We can also consider the case in which light will be put out partially. If we try to change the location of one of the interferometer's arms, then the path of one of the light beams will also change and, as a result, one will be able to witness the changes in the spot brightness visible on the screen. Right up to the point of total light quenching. So, that's theory.
- Exactly, that's one of the premises of wave interpretation.
- As can be seen in the diagram (Fig. 38), the beams of light reflected in the mirrors return towards a semi-transparent diaphragm. Each of those light beams carries the energy which may be used to, e.g. fill a hole in a piece of paper. If we deal with constructive interference, then there is no problem. The entire energy travels in the observer's direction and the observer may also burn the hole (let's say twice as fast as in the case of a single beam). Where, however, is the energy in the case of destructive interference? Then, on the observer's side, the piece of paper remains intact.
- Indeed, that is a very valid question, Ms Kamila.
- Is it then that in this case the law of conservation of energy doesn't apply?
- No, no, that is absurd! This law must apply at all times. One must rather look for some explanations. In the past, various scientists on numerous occasions would assume that they witnessed unexplainable decline or excess of energy. However, having conducted more precise examinations and upon thorough deliberations, the law of conservation of energy would always

prevail. Therefore, Ms Kamila, I recommend that we rather try to find that missing energy. Do you know where it might be?
- Yes, I do. First, I attempted to answer the following question; is energy generated where it is detected, across the entire area of interfering beams, or on the semi-transparent diaphragm? Then, I realized that, from the formal point of view, it is not important how far the observer is. If we assume that the observer may be anywhere, then it is possible that their location will be just behind the semi-transparent diaphragm. When we deal with destructive interpretation, the observer should not be able to see the light beam. Therefore, I decided to find the answer to yet another question; does the semi-transparent diaphragm heat up more during destructive interference than it is the case in the process of constructive interference, where the heating comes only from a slight absorption of light by a material medium?
- It won't be easy to determine in an experiment. {Professor interrupted}
- I am aware of that. It would require something more than a student laboratory. Because the hypothesis of the semi-transparent diaphragm heating up seemed to me a bit far-fetched, or at least difficult to prove in an experiment, I decided to look for a different explanation.

Kamila added the second semi-transparent diagram and the additional observer to the initial diagram (Fig. 39).

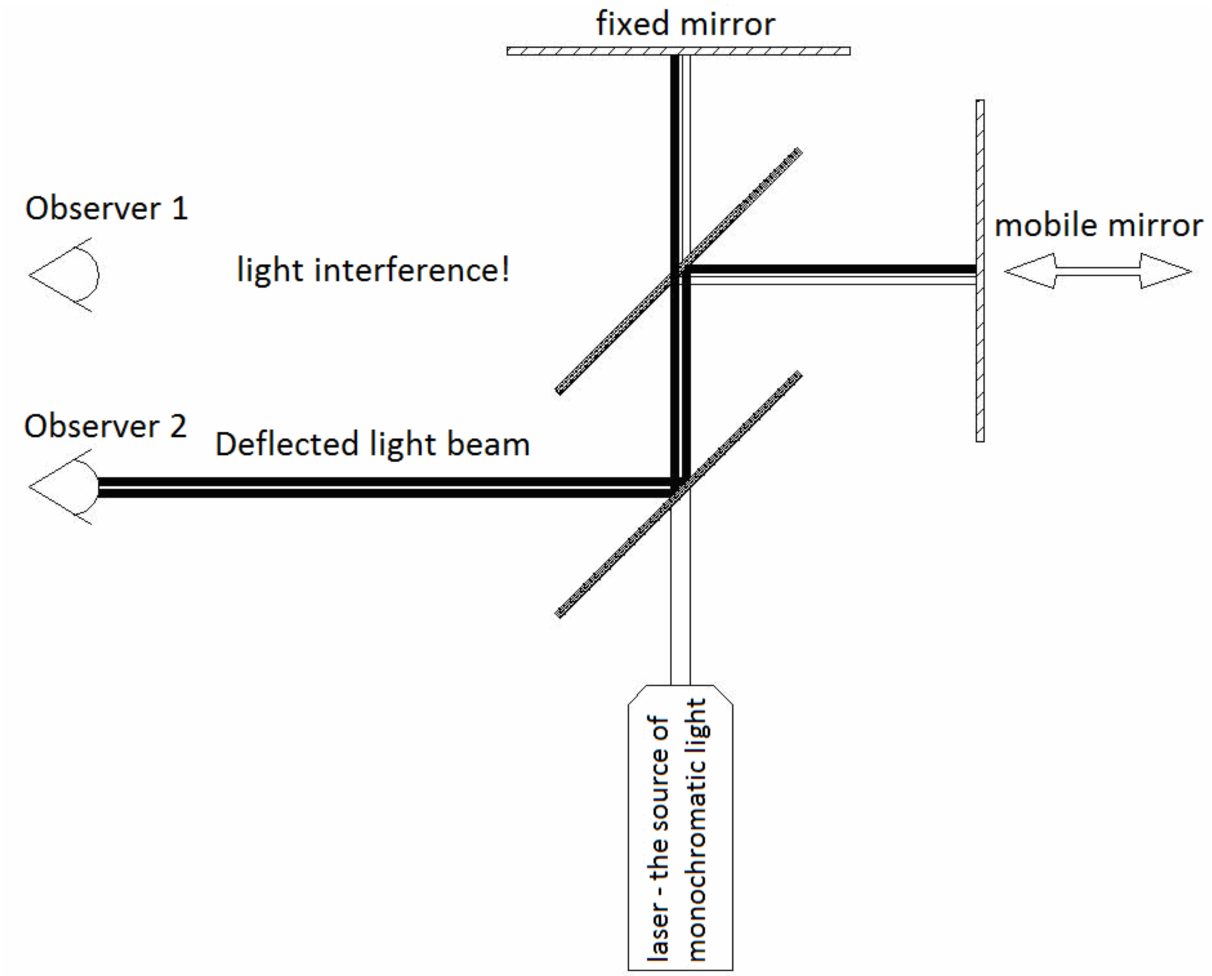


Fig. 39 Diagram of Michelson's interferometer with an additional semi-transparent diaphragm. Light passes through a semi-transparent surface, where it is divided into two beams of equal intensity. Then, having been reflected in the mirrors, it returns and, having reached the semi-transparent diaphragm, travels towards the source of light. The additional semi-transparent diaphragm reveals the beam of light returning towards the laser.

- Now I understand what you are trying to do. Unfortunately, the laboratory where you have classes is not equipped with interferometers. We will have to ask someone else to let us conduct the experiment or to do it themselves. I must admit, Ms Kamila, that your idea is genius in its simplicity. It is enough to add a single semi-transparent diaphragm in order to conclude whether during “destructive interference” the photons do not just return towards the source of light. Then, there would also be no problem with the disappearance of photon energy.
- Please note, however, that the experiment may hold many more answers. If we are talking about the phase shift, the general requirement for obtaining fringes based on the wave interpretation is the same for beams reaching the top and bottom observers. The process takes place regardless of whether we deal with constructive or destructive interference.
- That’s right, but what is the meaning behind this?
- If the wave interpretation is correct, then both observers should be able to see intensification or quenching at once.
- But that would mean that the problem of disappearing energy remained unsolved.
- Exactly! That’s why I suppose that light, depending on the conditions at the entrance to the semi-transparent diaphragm, sometimes heads towards the first observer, whereas on other occasions it is directed towards the second one. Then, as you have already noticed, there should be no problem with the law of conservation of energy.
- However, it would then signify the need to search for a completely different explanation, rather than interference, to explain the occurrences taking place there.
- You shouldn’t sound so surprised professor after all those experiments. {Kamila said jokingly}
- That was not funny Ms Kamila. I have completely no idea how to explain that in a different way.
- Don’t worry, me neither.
- Have you been able to find anything else on the internet, apart from inaccuracies regarding the interferometer?
- Not on the internet, however during my recent crystallography class, we were deducing Bragg’s formula for the purposes of explaining X-ray peaks. The professor was referring to the interference of X-ray beams. Shouldn’t the X-ray beam be coherent in this experiment?
- Hmm. All in all, the Bragg interpretation is the same as intensification and quenching of colors, with light reflected by thin surfaces. It consists in defining the difference in distances covered by an X-ray wave between beams reflected by different crystallographic layers. Depending on the angle at which the X-ray beam falls, the difference in routes changes accordingly. Therefore, for some glancing angles one may see peaks, whereas for others not.
- Indeed, however X-ray beams interfering after leaving the crystal come from various depths and, as a result, from different areas of the incident beam section. So, across the entire section of the incident beam there should be the same phase. The condition of temporal and spatial coherence must be met.
- Indeed. The exact same situation may be seen in the experience with thin layers.
- So, Bragg must have assumed that the X-ray beam is definitely coherent.
- There is no doubt about that.
- How does one obtain the X-ray beam? Could you please tell me about it?
- Of course. Didn’t you talk about it in your lectures?
- No, unfortunately not.
- Please pass me your notebook, then.

The professor took Kamila’s notebook and carefully drew the diagram of an X-ray tube, using it as an example to explain the tube’s operation (Fig. 40).

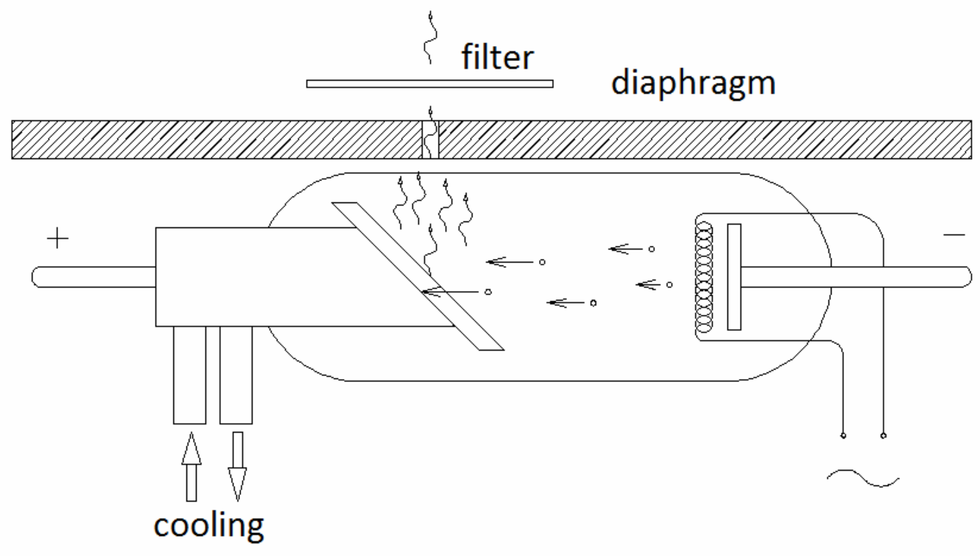


Fig. 40 The diagram of the X-ray tube's operation.

- The X-ray tube is nothing else but a vacuum bubble with two electrodes inside. Beside the negative electrode, there is a small spiral similar to the filament in Edison's light-bulb with an electric current passing through. When the temperature of the filament rises substantially, then, as a result of thermionic emission, an intensive cloud of free electrons appears, which are intensively accelerated in the direction of the positive cathode by means of applied voltage. Rushing electrons give away part of their energy to electrons located in the cathode's atoms (usually copper). This leads to the local excitation of electrons in atoms and the emission of photons, when their state reaches the initial level.
- I understand that the cathode's atoms don't use up their energy right after being excited.
- No, but the period of time between excitation and the emission of light is very short.
- Despite all that, however, the electrons in this type of lamp collide with the cathode surface at random moments in time and space.
- Of course, that's true. The electrons in the anode area appear spontaneously as a result of thermionic emission and begin to accelerate at different random moments in time, as well as with different initial speed.
So, they reach the cathode in a manner that is completely uncoordinated.
- Does the electron have any effect on itself on the way between the anode and cathode?
- Yes. The electrons push themselves away. Therefore, their speed and location in the process of passing between the electrodes will be subject to change in a way that is difficult to predict, and will depend on the location and mutual velocity of the electrons.
- In that case, the randomness of excitement among the cathode's atoms will be even greater.
- Not necessarily, because faster electrons catching up with the slower ones are then slowed down by them and vice versa. Faster electrons cause the slower ones to accelerate. So, the velocities of electrons during their movement should be leveled. However, here, we are far from the situation in which electrons would reach the cathode in a completely organized way. Even if the interaction between electrons would level up their velocities, then individual collisions between electrons and the cathode would still be fairly random.
- I understand that we cannot then assume that the X-ray beam is the beam of coherent wave.
- If we are talking about the X-ray tube, then we definitely cannot state that we are dealing with the source of coherent waves.
- If so, then why is it that in books Bragg's condition is being deduced in the application of the wave interpretation, i.e. interference? After all, the application of the said interpretation requires the condition of incident wave coherence to be met. However, the condition can't be observed.

- I don't really know. It seems that some of the book authors did not really pay too much attention to their contents.

- So I assume that this could only mean one thing. The formula deduced by Bragg was incorrect because it had no theoretical grounding.
- Not necessarily. It might be correct, however only in a random manner at best. We have already seen in the past that on occasions flawed hypotheses served as a basis for correct conclusions that were proved through experiments. It is hard to definitely say what is correct. I think that many scientists will not agree with your assertion that Bragg's condition could be incorrect. The entire concept of crystallography is based on that condition, as well as solid-state physics and many other theories which seem to rather exceptionally cope with providing the description of all that surrounds us. The rejection of Bragg's condition would be rather troublesome.
- I understand, however the fact remains that the matter in question will have to be rethought thoroughly so as to find a proper explanation of the surrounding phenomena. One, which would not be so easily discredited as the present one.
- I'm afraid that it won't be so easy as you might think, however you are completely right.

Filled with pride at being able to find yet another inaccuracy in the theory, Kamila raised her head. Suddenly, she caught a glimpse of the clock hanging over the entrance to the room, realizing that she was late for her next classes.
- I am really sorry professor, but I have already talked too much and I've got to go now! Would it be possible for me to pick your brains should I have any more questions?
- Yes, of course { Both departed hurriedly in opposite directions. The professor was also in a great hurry, however for a completely different reason}.

In the meantime, Kamila was off to her physics lecture, where the subject of discussion revolved around the movement of charged particles in electric and magnetic fields, as well as Faraday's law of induction.
As part of the lecture, students became familiarized with the formula for Faraday's electromotive force ε, created as a result of a shift in time of the magnetic flux Φ:

$$\varepsilon = -\frac{d\varphi}{dt} \quad (6)$$

$$\varphi = \oint_S \vec{B} \cdot \vec{S} \quad (7)$$

During the lecture, the discussion focused on problems in which a closed electric circuit of surface S was located within a homogenous magnetic field with induction B directed perpendicularly to the circuit in question. Then, one would obtain the following simplified formula (7)

$$\varphi = B \cdot S \quad (8)$$

The change in the magnetic flux occurred, depending on the discussed problem, via uniform change: in the value of magnetic induction B(t) or the cross section of the electric circuit S(t), which was easily determined in all discussed problems.

$$\varphi(t) = B(t) \cdot S(t) \quad (9)$$

For the magnetic flux defined in such a way it was only necessary to determine its time derivative in order to easily establish the value of electromotive force from magnetic induction. Kamila was quick to grasp the concepts discussed during the lectures, that is why she decided to solve the remaining problems, ones that had not been touched upon during the lecture, at home. When she found a moment of free time, she sat down and read through the first problem: *A metal bar of length L spins in a homogenous magnetic field of induction B perpendicular to the surface of the bar spin.*

Calculate the difference in potential between the ends of the bar, if it spins uniformly in relation to its end with angular velocity ω.

Right away she thought that there must have been a mistake. During the lecture, in the discussed problems, it was easy to determine a closed electric circuit and it was in relation to such circuits that the change in the magnetic flux was calculated. This time, however, there was no closed electric circuit (Fig. 41).

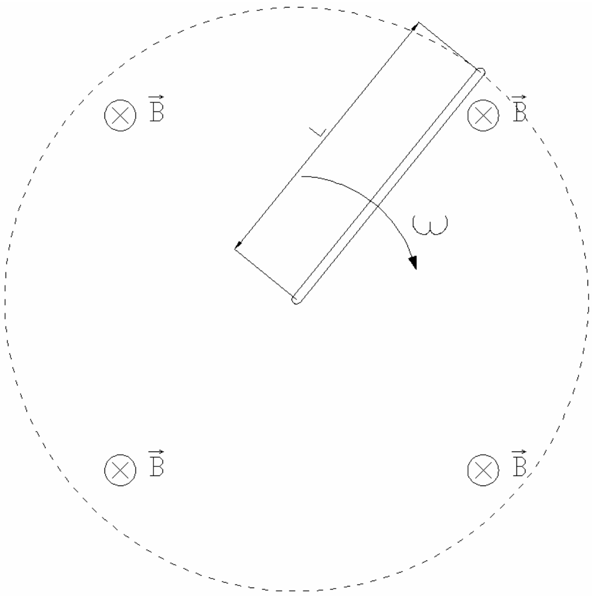


Fig. 41 Diagram related to the problem with a conductive bar spinning in the magnetic field.

She knew that the difference in potential to be calculated was nothing but voltage. Therefore, she expected that electromotive force ε (formula 6) needs to be established, which may be treated as regular voltage in Ohm's law. So:

$$\Delta V = U = \varepsilon = -\frac{d\varphi}{dt} \qquad (10)$$

Unfortunately, she did not really know how to calculate the shift in the magnetic flux since she could not fathom how to go about calculating the magnetic flux itself. After all, formula 7 contains the value of the closed circuit surface, and here there was no mention of any closed circuit. As a result, she decided to meet the professor the following day to find out how to solve the encountered problem. The professor was surprised that Kamila decided to come to him with such an easy problem. He approached the desk, where a piece of paper was lying, and drew a simple diagram (Fig. 42).

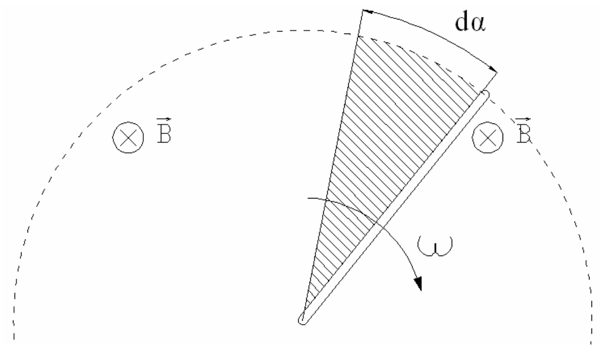


Fig. 42 The depiction of the surface marked by a spinning bar within time dt.

- Please, take a look. We may assume that within time dt the bar will move at dα angle. Then, the surface marked within this period of time will be equal to the one presented in the diagram. That is:

$$dS=\pi\cdot L^2\cdot\frac{d\alpha}{2\pi}=\frac{L^2\cdot d\alpha}{2} \qquad (11)$$

At the same time, we know that:

$$\omega=\frac{d\alpha}{dt} \qquad (12)$$

Therefore: $d\alpha=\omega\cdot dt$. Applying dα to formula 9 one obtains:

$$dS=\frac{L^2\cdot\omega\cdot dt}{2} \qquad (13)$$

- Now I understand! {Exclaimed Kamila} The magnetic flux will depend only on the shift in section dS, since magnetic induction B is constant in the problem, therefore:

$$\varphi(t)=B\cdot S(t) \qquad (14)$$

When we calculate the flux time derivative, then we will obtain electromotive force ε:

$$\varepsilon=-\frac{d\varphi}{dt}=-B\cdot\frac{dS}{dt}=-B\cdot\frac{d}{dt}\left(\frac{L^2\cdot\omega\cdot dt}{2}\right)=-\frac{1}{2}B\cdot L^2\cdot\omega \qquad (15)$$

- That was the exact point. Would you say that was difficult, Ms Kamila?
- No, it wasn't. It looks like a mathematical trick which allows you to calculate something, but you end up not knowing what it is all really for.
- Ms Kamila, what on earth are you talking about?
- I think I'm right, professor. You see, how does the said solution relate to the theory stating that the shift in the magnetic flux within a closed circuit generates electromotive force? By looking at this problem, I can clearly see that there might be obstacles in other cases as well. When the electric circuit is not closed, as is the case in this problem, but the shift may be seen only with regards to the value of magnetic induction B, or the electric system is not located on a flat surface, how do we then determine section S in formula 7? Moreover, I can also see a problem with trying to determine where exactly the voltage appears and what might be its value. Faraday's law (formula 6) only

determines the appearance value of electromotive force just as if it was induced within the entire electric circuit in a miraculous way. It does not determine the value of voltage that would be generated in any given area of the circuit. With such doubts in mind, I didn't really know how to go about solving this problem. Therefore, I came to you. Unfortunately, your solution doesn't dispel my doubts.
- Did you try to solve this problem in a different way?
- Yes, indeed. That's why I came to you. To see if my line of reasoning was correct and what would come out of it.
- I am all ears, then.
- Let's start with the premise that the bar consists of free electrons which may move with ease within the bar as well as other parts of the atoms. I will treat the latter as immobile positive cores.
 Is it the correct assumption?
- You can safely accept it as correct. It is in line with the present commonly accepted understanding of conductors. Please, carry on.
- So, I assumed that, since the bar moves within the magnetic field, then other free electrons and positive atom cores must also be able to move there in a similar manner. Based on my assumption, their velocity in relation to the magnetic field is equal to the tangential velocity of the bar. So, the further it is from the rotation axis, the bigger it becomes.

$$v_s = \omega \cdot r \qquad (16)$$

- That's not entirely true. From a theoretical standpoint, it is assumed that atoms oscillate around their average position and the higher the temperature of the body, the more intense the oscillation. This motion will overlap with the tangential velocity of atomic cores. What is more, the velocity of free atoms is even greater. We can assume that their average velocity at a given point will be equal to the tangential velocity of the bar.
- I understand. {Kamila pondered over the subject}
- Please, carry on Ms Kamila. Your assumption related to the velocity of free electrons, as well as atomic cores, is highly acceptable.
- Since free electrons and positive cores move within the magnetic field, I assumed that the Lorentz force affects them. At the same time, I will set out to consider only the motion of electrons because the motion of cores would result in the alteration of the bar's shape.
- Good point.
- When electrons are affected by the Lorentz force in one direction, they then try to accumulate at one end of the bar. At the opposite end, one may notice deficiency in that regard. This is how the difference in potential is created, i.e. voltage.
- If we factored in only the Lorentz force, then all conduction electrons would be stored at one end, wouldn't they?
- That is true. However, shifted electrons create the magnetic field in the bar, which subsequently generates the second force that pushes them away (Fig. 43).

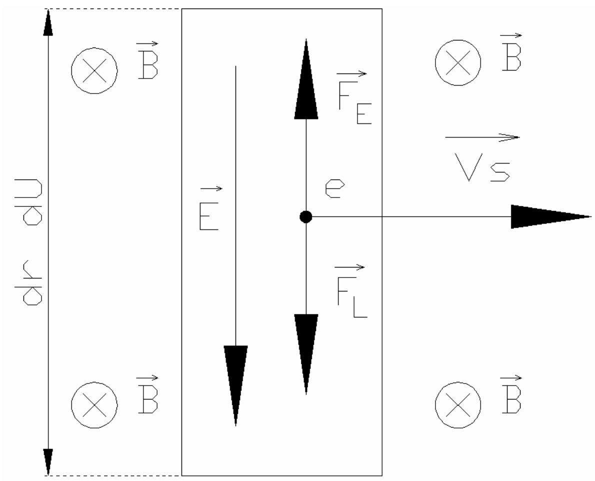


Fig. 43 The diagram of forces affecting free electrons in Kamila's solution.

Kamila continued:
- So, electrons are in motion until the net force reaches zero. When it happens, equilibrium is created and static electrons are not in motion any more. The above diagram (Fig. 43) presents a bar piece with length dr located at an r distance from the axis of rotation. Electrons move with v_s velocity within the said distance (formula 16) and are affected by the Lorentz force:

$$F_L = e \cdot v_s \cdot B \tag{17}$$

At the same time, as a result of heterogeneous decomposition of electrons within dr distance, dU voltage is generated which then enables the creation of the electric field defined as:

$$E = \frac{dU}{dr} \tag{18}$$

The created electric field generates electric force:

$$F_E = E \cdot e = e \cdot \frac{dU}{dr} \tag{19}$$

- That's very clever, Ms Kamila. Now I understand your point of view. You intend to compare both forces and deduce a formula that would enable us to calculate dU:

$$dU = v_s \cdot B \cdot dr = \omega \cdot r \cdot B \cdot dr \tag{20}$$

- Exactly, electrons will be in motion until the net force reaches zero. Then, every dr section will have a corresponding dU voltage value. If we add all dU values together, we will obtain U total voltage. So, we will get the following:

$$U = \sum dU = \int dU = \int_0^L \omega r B dr = \omega B \int_0^L \;\; = \frac{1}{2}\omega B(L^2 - 0^2) = \frac{1}{2}\omega B L^2 \tag{21}$$

- You see! That is exactly what I got in my solution (formula 15). {The professor seemed surprised} It seems that your way of thinking is also correct.
- Not necessarily.
- What do you mean?

- Only now have I realized that there might be a problem. Both solutions provide the same results, however from a physics standpoint they are not equal. First of all, however, I would like to point out that my solution copes really well with the doubts mentioned before. For every section of the electric circuit, even the smallest one, one can define relative movement between the magnetic field and a conductor and, based on that, determine the Lorentz force that has an effect on free electrons. Then, having defined the force, one can calculate the local rise in dU voltage that should occur in a steady state.
- We would then be able to establish where and what voltage will be induced, instead of only generally defined electromotive force. That's really clever, Ms Kamila. I must admit that I'm impressed. It must be said that your solution holds greater value than mine.
- It's not about the value at all, professor. It's about the meaning defined from a physics standpoint. Your solution only refers to the concept defined by Faraday and it's based on attempts to establish the shift in the magnetic flux which induces voltage. As if the shift in the magnetic field created voltage, which would subsequently put charges in motion.
- Indeed, that really happens. Varying magnetic field creates the electric field, which then facilitates the flow of current providing that the electric circuit is closed.
- And that is how you were applying Faraday's law to your reasoning (formula 6). However, this approach required you to come up with a trick based on defining the shift in dS section. Now, there is no shift in the electric circuit section in this problem. By the way, there is no closed electric section at all. So, from a physics standpoint, your solution is extremely far-fetched, and therefore doubtful. Regarding my solution, however, one doesn't have to refer to things that are non-existent.
- Hmmm. From a physics viewpoint, your solution seems to be much more feasible as it goes right to the root of the subject.
- I am glad that you appreciate that. However, I think that the issue of interpretation related to the acceptance of my reasoning is far greater. Have you noticed where the problem might be yet?
-The professor took a closer look at Kamila's solution and, after a moment of deliberation, concluded:
- Indeed, there is the difference in the cause and result order in your line of reasoning
- Exactly! The relative movement between the charge and the magnetic field caused by the movement of the conductor or magnetic field lines results in the occurrence of the Lorentz force that affects electrical charges (The change in value of magnetic induction B creates the local shift of magnetic field lines!). The force is the reason behind the movement of charges, which, only after the shift, create voltage.
- So, in your reasoning voltage is a consequence of moved electric charges influenced by the Lorentz force. The vital premise of my assumption, however, focuses on the movement of charges as a consequence of the creation of voltage induced by Faraday's law.
- Indeed! And what would happen if there were no charges within the space of the varying magnetic field?
- Following your line of reasoning, there will be no induced voltage either, since there will be no charges which could be moved and could therefore generate voltage or the electric field.

The professor pondered over the consequences of the question posed in such a way and after a long pause exclaimed:
- But that's absurd! It cannot be true. If that conclusion were to be true, then the electromagnetic wave could not exist, which, after all, moves in a vacuum. In the modern version of Maxwell's theory a varying magnetic field induces the electric field, whereas a varying electric field induces the magnetic field, etc. All of that takes place in a vacuum! This way, the electromagnetic wave is created which is propagated with constant velocity. We are talking about the speed of light for which the vacuum is no obstacle whatsoever.
- I understand that the waves you are talking about are the same as radio, radar and microwave waves, etc.? Something, we have already discussed.
- Yes, also now the concept of light is explained in the same vein as electromagnetic waves. It is a classic approach to the problem related to the nature of light. Only after the experiments conducted

at the turn of XIX and XX centuries were the scientists forced to accept its present dual nature.
- I remember that you spoke about it before. However, the experiments carried out in the laboratory did not hold any proof that light has wave properties, not to mention, dual ones. If we want to treat the so-called electromagnetic waves as equal with light, then they must be something else. If, however, they turned out to be something else, then your doubt would be unfounded.
- Indeed, that would not be the best counterexample to the conclusions derived from your solution. Nonetheless, with present experimental facts, it would be ludicrous to state that the so-called radio, microwaves, etc. do not exist. Are they really electromagnetic waves as posited by Maxwell? {Maxwell's theory related to the stress and movement of ether, so it is safe to assume that those would not be the same waves as they are described at present!} Unfortunately, we are at the moment unable to explain those phenomena in a way that does not involve referring to the existence of electromagnetic waves.
- Then, is my way of thinking incorrect with regards to this problem?
- Your solution seems to be very thorough and well-thought. What is more, it touches upon the essence of the problem. Much more so than the general assumption that the change in the value of the magnetic flux induces the electric field (electromotive force) at an unspecified location within the electric circuit.
- This reminds me of the words spoken by my previous teacher, who said that *physics is comprised of many laws of nature. Some are very general and seemingly mysterious but are easily solved and understood based on more basic and elementary laws. And it is those laws that are the real reason behind the observed phenomena.*
- That is true, Ms Kamila. Let's take Archimedes' principle. What does it describe?
- Everybody knows that, professor. Archimedes' principle describes the upward buoyant force that is exerted on a body immersed in water. It is equal to the weight of the fluid that the body displaces.
- Right, doesn't this principle sound too mysterious?
- Hmmm. If one were to think about it for a while, it would be safe to assume that for someone who is not familiar with Pascal's law and is not able to calculate the force of pressure, Archimedes' principle may really seem fairly mysterious.
- Please note that in this instance we may be faced with similar dilemmas, as was the case with the direct application of Faraday's law.
- The professor turned around a piece of paper lying on the table and proceeded to draw a diagram (Fig. 44).

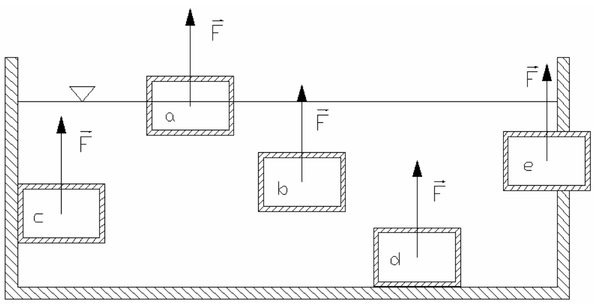


Fig. 44 Diagram presenting Archimedes' force exerted on a body immersed in water.

- Archimedes' principle, as you mentioned, describes the force exerted on a body immersed in fluid whose value is equal to the weight of the fluid that the body displaces. In example 'a' the volume of displaced fluid will be part of the case's volume, which should be easy to determine. Whereas, in examples 'b', 'c' and 'd' the matter of the volume of displaced fluid is very easy and equals the volume of the entire case. With regards to example 'e' , the volume of displaced fluid is a moot point, especially if the wall, through which the case goes, was not vertical.
- Similar to trying to define surface S while calculating the value of the magnetic flux in the case of

open circuit, or the one not located on the same surface?
- Exactly. Meanwhile, Archimedes' principle (Fig. 44) does not describe the actual behaviour of the case in examples 'c', 'd' and 'e'.
- How so?
- The professor drew a similar layout of cases. This time, however, instead of Archimedes' principle, he marked the point of exerted pressure based on Pascal's law and changing in proportion to hydrostatic pressure (Fig. 45).

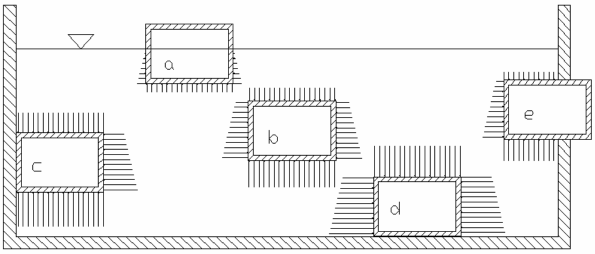


Fig. 45 Diagram presenting pressure exerted on cases immersed in fluid.

- Now I understand what you meant. In the case of examples 'a', 'b' or 'c', it is easy to calculate the buoyant force, which is applied upwards, by adding up all of the forces to be found on the case's surface. Because the pressure below the bottom of the case is higher, therefore the hydrostatic pressure exerted on the bottom surface is higher than the corresponding one exerted on the top surface. As a result of all the forces the net force is created, which is also known as Archimedes' force. However, in the case of 'c' and 'e', the pressure exerted on the side surface is not compensated with the pressure from a different direction. Therefore, the case will be pressed against the wall of the container, the fact that is not provided for in Archimedes'principle.
- Indeed, but that is not everything. Example 'd' is really interesting. Let's imagine that we have a case with average density lower than the density of water. If we wanted to immerse it in an aquarium filled with water, then we would have to take steps to counteract the buoyancy force which, in this case, would make it difficult for the case to be moved, while also pushing it upwards.
The buoyancy force will be present all the way down to the bottom. There, a seemingly magical thing happens. If the case is smooth, just as the aquarium, it can then be placed in such a way that there will no longer be any liquid under it. Then, one would see that the case would not only stop moving upwards, but, more significantly, that it would be pressed downwards.
- Interesting. I didn't pay attention to that before, however, it really seems impossible to solve this matter based on Archimedes' principle. This case shows how deceptive some of the principles might really be. Only by going deeper to the core of the phenomenon, i.e. forces which are really pushing against the immersed case, is one able to see the bigger picture, portraying all nuances that seemed so mysterious before. However, the same could be said about Faraday's law. His law is equally broad in nature as Archimedes' principle and it can also be explained by referring to the original cause of observed phenomena, i.e. the Lorentz forces, having a direct impact on charges.
Whereas Archimedes' principle may be regarded as a consequence of pressure forces exerted directly on the surface of the object immersed in liquid, Faraday's law is nothing else but a consequence of the exertion of the Lorentz forces on electrical charges.
- Well, following this line of reasoning I would not only have to admit that you were right regarding the problem with a conductive bar spinning in the magnetic field, which I have already done, but I would also have to admit that it is a completely correct solution, which refers to the actual cause of the difference in potential observed in such an experiment. However, it is in contradiction with the concept of electromagnetic waves travelling in the so called vacuum!
- Given that, we must now try to decide whether there are any other inconsistencies in Faraday's law such as those in Archimedes' principle that you recalled? In the commonly accepted

interpretation of Faraday's law, a varying magnetic field causes the emergence of the electric field (voltage). The faster the change in value of the field flux, the bigger the field becomes. Subsequently, voltage is generated which causes the flow of current.

Ohm's law gives us the following:

$$I=\frac{U}{R} \tag{22}$$

Therefore, current which will run in the conductor, located in a varying magnetic field, will be dependent on the value of electrical resistance. Is it then that in superconductors, where the electrical resistance equals zero, critical current will be induced at all times, regardless of the volume of change in the magnetic field? (In theory, the current would be infinitely substantial, however such currents do not exist in superconductors.)

- No, it would be absurd! If it were the case, then, regardless of the speed at which the magnet would be brought closer to the superconductor, it would always generate the same magnetic field. This field would be dependent only on the geometry of the superconductor and density of the critical current, and not on the distance or speed at which the magnet would be drawn closer to the superconductor. You may not know this, but the superconductors are characterized by a low electrical resistance in the case of alternating voltage. The higher the frequency of the varying electric field, the higher it becomes. Therefore, I think that the critical current won't necessarily run in the superconductor straightaway.

- And yet, you might be wrong, professor. During one of our lectures, we discussed the problem in which a conductive ring was located in the magnetic field whose value would change linearly in time. This means that the magnetic flux would also change linearly in time (formula 9). According to Faraday's law, the induced voltage would be constant. As a result, one would be able to bring the magnet closer to the superconductor so as to, in accordance with the theory, induce constant voltage whose value would be dependent on, e.g. magnetic force. Then, the superconductor would continue to be characterized by zero electrical resistance and my previous remark regarding the induction of critical currents would still be valid.

- Indeed, my remark has not been thought out. In such case, I am wondering whether a varying magnetic field acts as a voltage source the way it was reflected in your calculations based on Faraday's law. Or maybe, it should be viewed as a source of current, which would serve as a better way to describe its behavior in superconductors? Moreover, were it to be a source of current, then the concept of the Lorentz force being responsible for the movement of charges would seem to be a more plausible explanation of the phenomenon than the assumption that it was electromotive force, generated by induced electric field, which influenced the movement thereof. Superconductors have a certain quality which means that current is induced in them in such a way as to generate a zero magnetic field within each superconductor, or one that would enter it in the form of the so called vortexes (type-II superconductor). So, your example with the induction of voltage in the superconductor might not be the best because the superconductor is a unique material and it behaves uncharacteristically, while reacting to the external magnetic field.

Meanwhile, in the case of regular conductors, it is assumed that conduction electrons move in random directions determined by each collision. Within that period of time, they move at considerable speed and cover distances that substantially exceed those between the conductor's atoms. The average velocity of electron movement equals zero. In the case of appearance of an additional electric field within the conductor, an additional external electric force is exerted on charge carriers. The force in question alters the average values of the velocity of free electrons, providing them with resultant velocity in the direction of a charge moving within the conductor, which is observed as current flow. A similar effect may be obtained in the event of appearance of an additional magnetic force having an effect on charge carriers. The Lorentz force replaces the electric force under such circumstances, while the premises of Ohm's law are still retained.

So, attempts to differentiate whether in this instance we are dealing with voltage causing the appearance of current, or the Lorentz force causing the movement of charges, may be hard to determine experimentally.

- Finally, we always end up with the same conclusion, professor. Faraday’s law of induction (formula 6) is basically the same as the Lorentz force and if we attempted to consider them as both having a simultaneous effect on free charges, then our assumptions would be wrong.
- Of course! It would be the same as trying to simultaneously take into account Archimedes’ force and pressure force in one’s calculations. It is also worth noticing that the pressure resultant force determines exactly at which point and what forces are exerted on the object immersed in liquid. Contrary to the Archimedes’ force formula. Similarly to the Lorentz force in your line of reasoning which enables us to accurately determine the location and the volume of voltage generated in the analyzed electric circuit. However, such line of reasoning will force us to re-examine the actual nature of waves, e.g. radio waves, microwaves, etc. Especially, since we assume that those are the phenomena of the same nature as light.
- Even more so, when we keep in mind that the experiments that I conducted in the laboratory undermined the wave interpretation in some of the most essential experiments related to light. {Added Kamila}
- Indeed, your experiments put a question mark over the widely accepted interpretation of light as a wave. However, I must remind you that such aspects as the lack of mass and a precisely determined significant speed of light in a vacuum become an even greater mystery, when we reject the wave nature of those phenomena. That is exactly why it is so hard, if at all possible, to abandon the current wave interpretation of light. I’m not sure if the scientists are prepared to reject the wave interpretation altogether? I don’t really know how to come up with a suitable replacement for the theory in question. At the moment, the only solution I can think of is continuing to look for further experimental evidence and other inaccuracies related to light, as well as other accepted theories, which would give us some additional clues in the search for correct explanations of the observed phenomena.
- All in all, it seems that there are no contradictions in relation to my solution of the problem?
- No, however, it contradicts the idea of an electromagnetic wave (more specifically, the inducement of electric field in vacuum caused only by an alternating magnetic field without moved charges). I do not know how to explain this, but I cannot prove you are wrong.
- I understand. In that case I will consult this solution with my lecturer ;-). I think it is time to go, it is getting late.
- Till our next meeting Ms Kamila.
- Goodbye professor.

The professor stood up and while pacing the room, began to wonder about the conversation that had just ended. He knew that the conclusions from Kamila's experiments contradict the contemporary comprehension of micro-world phenomena. He understood that these hypotheses of: light duality, wave of matter and even more so, the probability wave, are highly absurd and indirectly result from the wave-corpuscle interpretation of the nature of light. He remembered hearing a theory from many authority figures, that such phenomena may not be explained by classical (mechanistic) physics.

- Is it indeed so? {He thought}

He knew that in Young's experiment with single photons or electrons, one obtains individual, it seems chaotic, points on the screen, which only after a longer exposition time become well-known fringe images (Fig. 46).

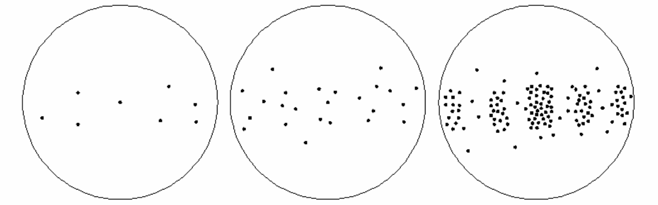


Fig. 46 Result of plate exposure to single photons or electrons in accordance with Young's experiment [4, 5].

Such a result may not be explained by interference. Single photons projected on the screen may not interfere with other photons projected onto a different place on the screen and at a different time! That is why, the current wave interpretation of this experiment could have been discarded long ago, if only physicists were able to admit they were wrong. Instead, an absurd theory was created, that every photon or e.g. electron interferes with itself on the basis of „wave probability" interference [5] - and such a statement is sheer gibberish that does not explain anything! Meanwhile, experiments with single photons or electrons also prove that there is no interference in this experiment!

Nonetheless, the professor reminded himself about Young's experiment with the use of single particles, because it shows that the final explanation of this phenomenon must have a probabilistic description. However, it may also be deterministic in nature. {No matter how many times Young's experiment would be conducted, one always obtains the same results. The exact same thing may be observed in heat theory, although it is a deterministic phenomenon from a classical point of view.}

- But how to explain the creation of fringes on the screen in this experiment from a classical point of view? {He asked himself}

While pondering on the answer to his question, the professor paced around his study. Then, in the corner of the room, he noticed a triangle used to visualize Gaussian's curve (Fig. 47).

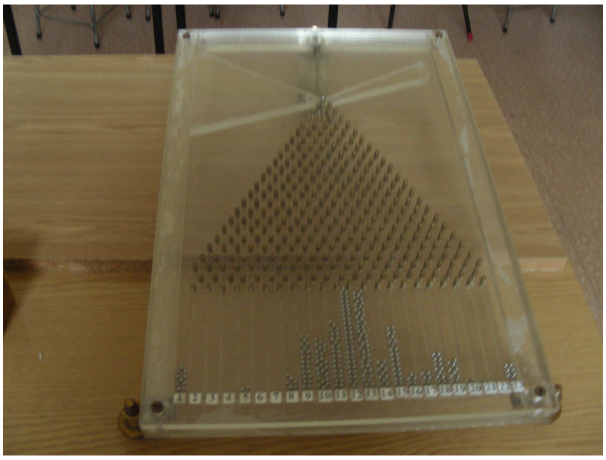


Fig. 47 Probabilistic arrangement of balls in the triangle

He quickly realized that the balls at the bottom of the triangle may represent light intensity for an individual fringe in Young's experiment. At each stage, the change in the direction of the balls movement, no matter left or right, is random from one's point of view However, in fact, it is a deterministic process. The same may occur when dealing with light. From previous experiments, one may conclude that light, while travelling beside every single edge, interacts with matter and divides into a few beams, which we then observe as fringes on the screen. At that moment, the professor assumed that on the surface of each solid body there is an electric field. It would be a local field that came from averaging the interactions of external electrons with a positive atom core and, perhaps, one that would possess a high electric field intensity or gradient of that field. The mentioned electric field possesses a certain average arrangement along the surface, which probably fluctuates randomly. Next, he assumed that when light travels through a local electric field fluctuation, then depending on its phase, it can be deflected from its movement direction perpendicularly to the edge (Fig. 48). Assuming that such a deflection is a constant for each photon movement disruption, we should be able to obtain single photon fringes on the screen (Fig. 49).

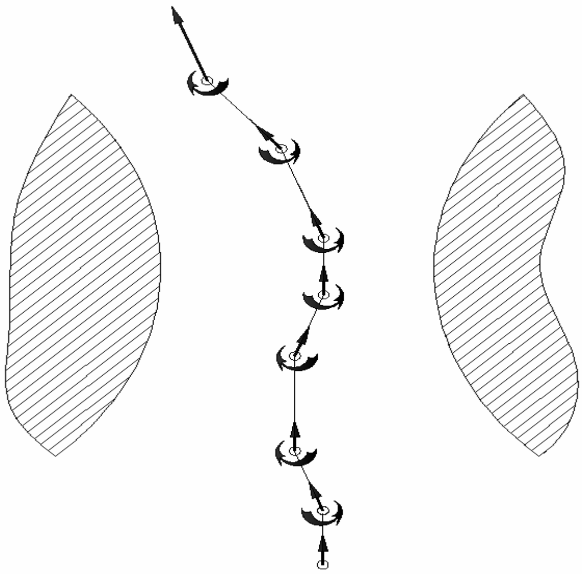


Fig. 48 Photon behavior diagram close to the edge (**only a hypothesis!)**

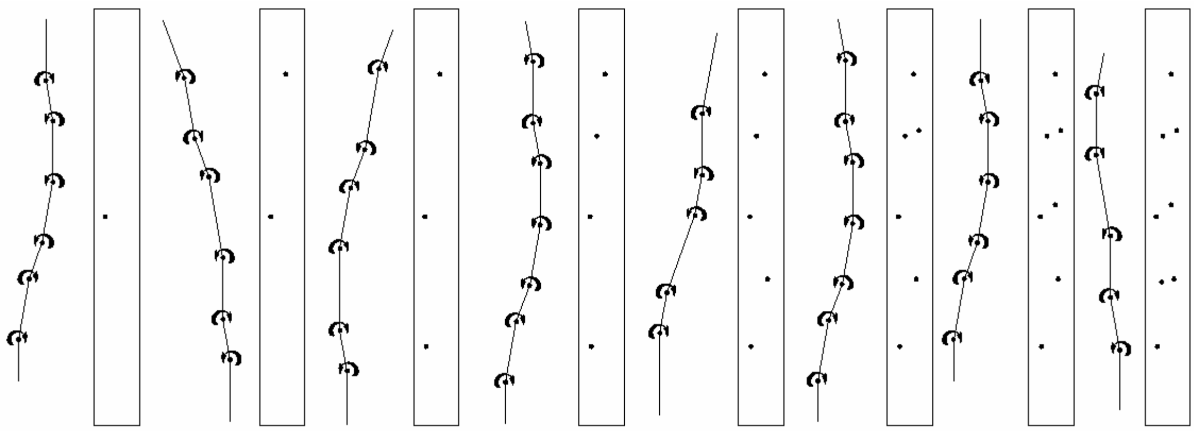


Fig. 49 Probabilistic mechanism of the change in direction of photon movement at the edge, which leads to the creation of fringe images.

The intensity of these fringes would have a similar pattern to that proposed by Gauss, which serves as a better explanation of the change in brightness of individual fringes than the statement in which the change is allegedly due to the difference in distance from the apertures [2]; an assumption clearly contradicting the experiment!

- Is the image of the phenomenon that I have created true? That I do not know, but time will tell. {The professor wondered on} Nonetheless, this model is more suitable for the assumption of brightness for individual fringes than the interference theory. What also results from this, is a dependency in the placement of the fringes on the material the edge is made of. The edge on which light is divided. One may assume, that for different materials the fluctuation of magnetic fields on the edge can have a different intensity of occurrence and size. Also, it is easy to imagine, that the curvature of a surface would have an impact on the amount and strength of the electric field disturbance near the surface. It is also possible that the image seen on the screen would depend on the temperature of the edge or aperture! Nonetheless, this interpretation was also problematic for the professor. Although it is easy to imagine the existence of a local voltage on the surface of every solid body, he did not know of an experiment in which light would have to directly interact with an electric field. If something like this were to happen, then light would have to interact with bigger electric fields than ever researched. Maybe a higher gradient of the field is more essential than the size.

However, in physics an absurd theory of a probability wave is most commonly accepted. Just as we are now amazed at the way it was possible to believe in an electrical or heat fluid, or other such naive theories, next generations might laugh at our comprehension of the micro-world. Especially that so many "well established" research facts concerning light turned out to be false, as it was shown in recent experiments. An accepted hypothesis of the existence of waves of matter and other assumptions led to the creation of a theory, which is sometimes astonishingly true to the experiments. (At least this is something written in textbooks, that the assumptions of quantum mechanics are true to the experiments!??)

- How is it possible, with such absurd assumptions on which this theory is based!?

The professor shouted out loud and continued to pace around the room pondering over the history of physics. Then, he remembered that the theory of Copernicus was less accurate in predicting the placing of celestial bodies than that of Ptolemy and together with its updated versions [6]. Even if the second one in our view is absurd and false. Of course, Ptolemy's theory did not cope well with the prediction of changes in obscurity of celestial bodies, such as the moon. Astronomers of that time were mostly interested in the placement predictions of objects they saw (where do they see them?), at the same time ignoring how they could them. In Ptolemy's model, "celestial" bodies moved in circles in a uniform motion, because due to the beliefs of that time, this was the only motion acceptable for godly objects. Copernicus was of the same persuasion and therefore his model did not predict the placement of planets correctly and was less accurate than that of Ptolemy. So Ptolemy's model was not discarded because his measurements were not precise. On the contrary! The fact that, at that time, he was able to predict the placement of celestial bodies more accurately than Copernicus was an argument in favor of his theory. However, the less accurate prediction of Copernicus was an argument against his theory. Ptolemy's theory was discarded with a lot of hesitation because of Galileo and Kepler's discoveries. The main problem was Aristotle's authority and his vision of how the world worked, were Earth was the natural centre of everything and towards which everything material naturally gravitated. However, cosmic objects moved continuously in a uniform motion, not influenced by Earth. New theories were hard to accept for the elites of that time, because they forced them to discard their whole outlook on life. The same went for "infallible" church doctrines, which resulted in understandable resistance.

- And how is it today? {The professor stopped to think for a moment, but then went back to his remaining thoughts}

If Ptolemy's theory was incorrect, and we now do not have any doubts whatsoever about that, then how was it so good with measurement data? Then, he realized that Ptolemy's system is a flat one, just the same as Copernicus'. With regards to such a system, an observer being in the centre, on Earth, has no opportunity to observe the moves of celestial bodies from "above". He only sees them as projections in Earth's direction (Fig. 50).

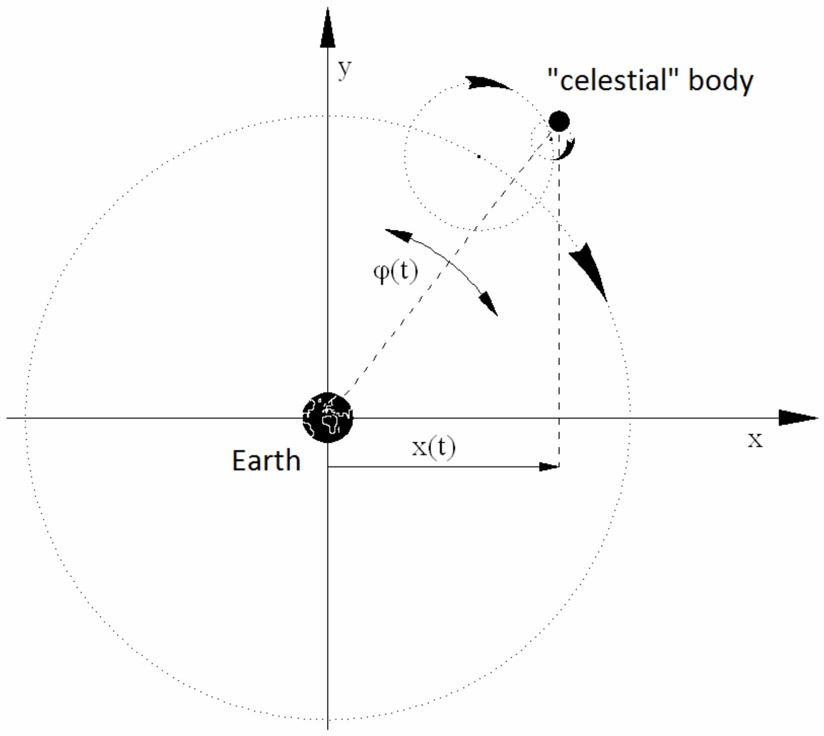


Fig. 50 Movement of celestial bodies in Ptolemy's model

The projection of a circle uniform motion onto a straight line placed on the surface of this motion is a sinusoid function. However, the composition of such circle motion projections results in a sum of the same functions. Finally, it creates the Fourier row, which has the capability to match every periodical function. Undoubtedly, the movement of celestial bodies seen from Earth is approximately a periodical one and may be quite accurately described by Fourier's row. However, the observer located on planet Earth does not see the projection onto the straight line directly, he sees a projection towards a point represented by Earth. This finally creates a description of placements in the form of angle changes, e.g. φ(t), not x(t). That is why, the function received does not exactly correspond with Fourier's row, but has an equal ability to match the experiment results with the choice of such parameters as: radiuses and angle velocity for individual circle motions. Although in this case one does not use Fourier's row directly, the more circular motions present in the description of a celestial body in Ptolemy's model, the more accurate measurement data can be matched. The professor understood, that for any considered theory, the compatibility to the experiment is not proof enough of it being true. If one uses such mathematic mechanisms, as e.g. Fourier's row, then the "perfect" compatibility to the experiment would not be the result of the correctness of considered hypothesis, but the properties of the used mathematical apparatus.
-So how is it now? Can a sophisticated quantum mechanics mathematical apparatus perfectly match the results received in the experiment? Is the textbook declaration of experiment compatibility a result of the adopted hypotheses, even if they are illogical? How sensitive is the model of mathematical quantum mechanics to the discarding of the hypothesis concerning the existence of waves of matter, when the conducted experiments on light showed that such a hypothesis should be discarded? Is the treatment of e.g. electrons as waves of matter (sinusoid functions), and next the "addition" of such waves in order to obtain one common quantum state, tantamount to creating something very similar to Fourier's row? Maybe this is the main cause allowing the "perfect compatibility" with the experiment!
- And what of electromagnetic waves? {The professor continued} Do they really exist? Especially when they are treated as the same construct as light. However, can light be just a particle? If so, then what of its mass? This would contradict the theory of relativity, in which there is no material

object which can reach the speed of light. Then is Einstein's theory true? It seems well established with the use of experiments. Nonetheless, when there are such blatant discrepancies between the experiments and light theory, which is the core of other assumptions, then where else could one also find such surprises?

The professor, overwhelmed with so many doubts, sat down and felt really worried, because, in the end, he did not know what was to be believed. He could not discard the conducted experiments in the laboratory, while he did not know how to fully explain them either. Understanding the significance of these discoveries, he felt even more worried.

[1] Andrzej Kajetan Wróblewski, „Prawda i mity w fizyce”
[2] S. Kryszewski, „Mechanika Kwantowa”
[3] R.P. Feynman, R.B. Leighton, M. Sands, „The Feynman lectures on physics”
[4] Michał Gryziński, „Sprawa Atomu”
[5] D. Halliday, R. Resnick, J. Walker, „Fundamentals of Physics”
[6] Andrzej Kajetan Wróblewski, „Historia Fizyki”

The presented work does not generate answers to doubts concerning quantum mechanics and the postulates on which this theory is based. On the contrary, it is more than certain that more doubts surfaced after reading it. These doubts are concerned a wider specter of problems than only those related to quantum mechanics. They are concerned with such questions as: What is light really?

Nowadays, almost every intellectual human activity is subject to the risk of going astray. That is why, the presented work was checked by fellow physicists at various times and stages of realization. Among those, there were some highly renown or less renown physicists, as well as very talented students. There were also two seminars devoted to the subject in question at Gdańsk University of Technology, so that the drawn conclusions could be exposed to scientific criticism. During those seminars many doubts as well as allegations surfaced, answers to which one may find in the presented work. The feedback was a great addition to this work. Finally, to this day the work has not been factually discredited and met with both positive and passive reception.

Sincerely,
Paweł Fiertek