Retention of a Double Slit Single Photon Interference Demonstration of Particle-Wave Duality[1]

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Abstract. Late May 2018 75 students of a grade 11 class observed a sequence of double slit demonstrations that culminated in a single photon interference demonstration and discussion using the PhET applet on quantum wave interference. In pairs students had to work out some of the measurements. Three months later, the first week of October and well after Summer vacation, 5 students were interviewed about the set-up of the experiment, what they had observed, and what had been concluded. In March 5, 9 months after the demonstration, other students were interviewed. Students were able to recall many of the details of the set-up and observations and of the discussion on wave-particle duality.

Introduction

In the past there has been great faith in the power of laboratory activities and teacher demonstrations to enhance the learning of physics concepts. However, reviews of the effectiveness turned out to be disappointing [1-3] and have shown that lab activities and demonstrations need to be carefully designed and embedded in lessons to realize cognitive benefits [4]. Therefore, we carefully scripted and evaluated our single photon interference demonstration. The experiment is portable, fitted in a travel-size suitcase and can be borrowed by secondary schools [5]. Last year we reported results of a study with this demonstration and 112 12th grade students and 5 teachers [6]. In this poster we report on a retention study with 68 grade 11 students.

Lesson overview

After introductory lessons on quantum physics which included the photo-electric effect and the de Broglie wave length, 68 grade 11 students took part in the following series of demonstrations intended to confront students with wave-particle duality:

1. spraying colored water (paint) through a double slit (several mm wide) using a common plant sprayer and observing the pattern;
2. a beam of parallel light rays through the same slit;
3. a short YouTube video of water waves passing a double slit;
4. laser light on a double slit;
5. a short video of an electron beam passing through a double slit with and without detectors (Dr. Quantum)
6. single photon interference using the experiment described below.
7. A discussion of results using the PhET quantum wave interference simulation to visualize the situation.

The demonstrations were led by the teacher but students were asked to individually predict for each demonstration which pattern will be observed on the screen, an image of the slits or an interference pattern. In demonstration 6 students were also asked to calculate the typical distance between photons with some guidance of the teacher and to perform some of the data analysis by hand before it is projected on the screen.

Please note that we got to this particular sequence of demonstrations as previous research [6] with just the suitcase demonstration indicated that students just kind of accepted the results blindly

[1] Hand-out for a poster session at the GIREP Conference, Budapest, 1 – 5 July 2019.

without much surprise. They needed to get more involved by actively predicting and they needed to be made aware of their own prior conceptions of particles and waves.

The single photon interference demonstration

Figure 1 shows a set-up of a double slit interference of single photons in a suit case which can be borrowed by schools. A laser beam passes through a filter which lets through only one out of 10^6 photons. With a laser of 5 mW and the slit only letting through about 15% the remaining intensity, the distance between successive photons becomes about 12 cm and at any time there would be only 1 or 2 photons between slits and detector. A biconcave lens between slits and detector spreads the beam. The photons are then counted at 300 positions in the 1,5 mm cross section of the beam. While counting, the *number of photons* versus *location* graph builds up on a screen (Figure 2) and is projected on the wall. A detailed technical description is provided in a paper [6]. The demonstration was followed by a teacher presentation and discussion of the PhET-quantum wave interference applet and concluded by the Dr. Quantum film.

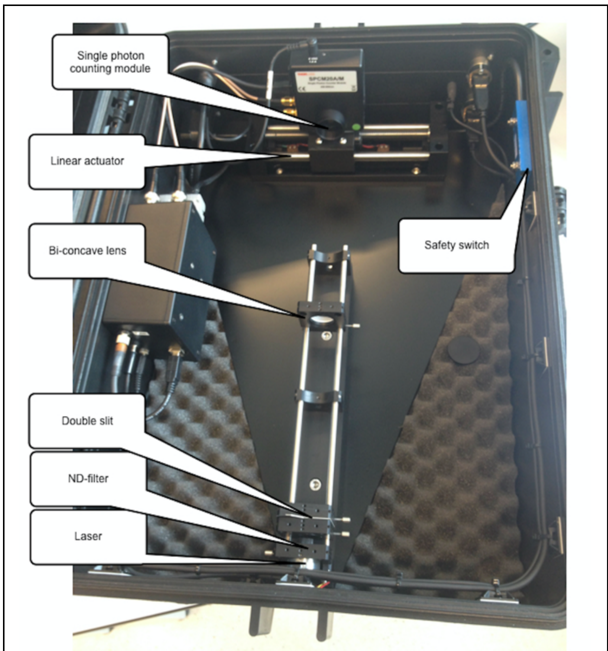


Figure 1 Single photon interference in a suitcase.

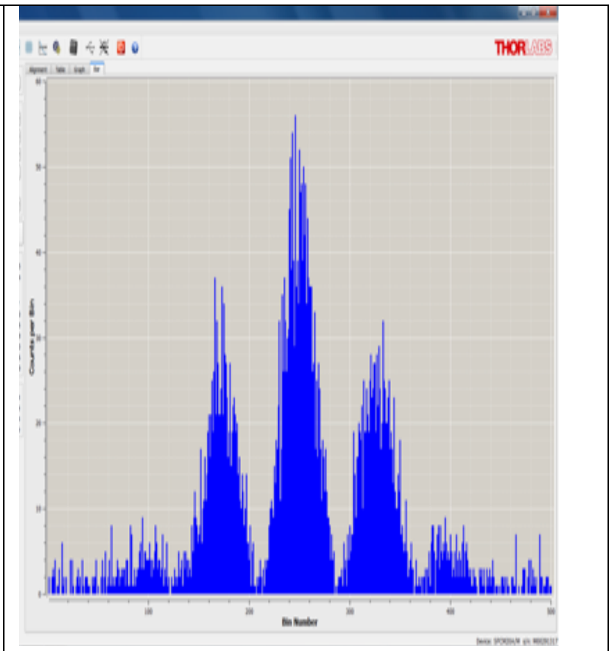


Figure 2 Display of results.

Single photons

What is the basis for our claim that this experiment is single photon interference? We calculate the density of photons in the light beam between the double slit and the detector.

The power of the laser is 5.0 mW, attenuated by a factor 10^{-6} this becomes $5.0 \cdot 10^{-9}$ W. The energy of one photon of 635 nm is:

$$E = hf = hc/\lambda = 6.63 \cdot 10^{-34}\ [Js]\ 3.00 \cdot 10^{8} [m/s]/(635 \cdot 10^{-9} [m]) = 3.13 \cdot 10^{-19}\ [J]$$

Through projection of a Gaussian laser dot on a double slit we determined that about 15% of these photons get through the two slits while the remaining 85% are reflected. The maximum number of photons reaching the screen per second is:

$$0.15 \cdot 5.0 \cdot 10^{-8}\ [J/s]/(3.13 \cdot 10^{-19} [J]) = 2.4 \cdot 10^{9}\ [photons/s]$$

These photons are spread out in a light beam with a length of $3.0 \cdot 10^{8}$ m so the typical distance between successive photons is about $3.0 \cdot 10^{-9} / 2.4 \cdot 10^{9} = 0.13$ m. That is 200,000 times the wavelength of the light of the laser. So interference with other photons seems unlikely. In present day physics single photons are produced in pairs while attenuated laser beams are considered as classical EM waves.

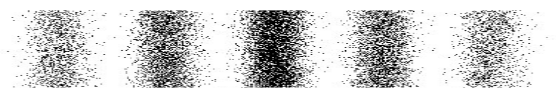
Tests

68 students took part in a written posttest after the unit on quantum physics at the end of the school year. Here we present only results on 10 multiple choice questions.

Items 1-5: We let matter particles or light go through a double slit and see at a screen behind the slit whether we get figure A or B as a result. The measurements of the slits are the same order of magnitude as the objects or wavelengths which we send through the slits. The area where light or matter hits the screen are indicated in black. We only measure on the screen.

A

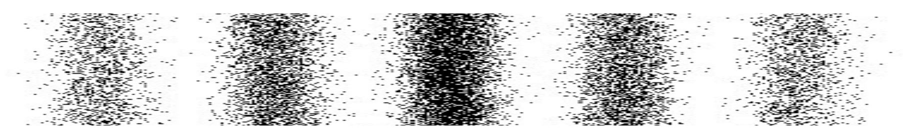
B



Indicate which of the patterns (A or B) most likely will be observed at the screen in the following cases:

1. We illuminate the slit with laser light.	16%A	84%B
2. We shoot small paint balls through the slits.	96%A	4%B
3. We shoot small bullets (1 mg) through the slits.	93% A	7%B
4. We shoot protons through the slits.	7%A	93%B
5. We shoot C_{60} molecules (nano-size) through the slits.	32%A	68%B

Items 6 - 10: A researcher carries out the double slit experiment. First he shoots a beam of electrons at the double slit and looks where these hit the screen. There is a interference pattern as shown below.



Choose for items 6 – 9 from the following key:

A. Nothing.
B. The minima/maxima come closer together.
C. The minima/maxima move farther apart.
D. The interference pattern disappears, there will be two maxima right behind the slits.

6. What changes in the interference pattern when the researcher will increase the velocity of the electrons? 40%A 44%B 16%C 0%D
7. What changes in the interference pattern when the electrons are replaced with particles of greater mass but equal velocity? 4%A 56%B 28%C 12%D
8. What changes in the interference pattern when the researcher lets the electrons go one by one through the double slit rather than use a beam of electrons? 82%A 4%B 6%C 12%D
9. Again the electrons are send one-by-one through the slits but now there is a detector at one of the slits to determine through which slit each electron goes. What is the change in the pattern on the screen? 16%A 0%B 0%C 84%D
10. Give a short explanation for your answer to question 9.

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Questions 6 and 7 were not answered that well. In the interviews it turned out that many students by the end of the unit had forgotten about the de Broglie wavelength and formula.

Interviews

10 Students were interviewed on video, part of them in pairs as interaction between them would make for a more spontaneous elicitation of their conceptions than an interview between the researcher and one student. The questions asked were: a) what is a particle, what is a wave, and what is the difference? b) remember the suitcase demonstration? What was the set-up? c) what did we observe? And d) how did we interpret results? During the last question the PhET quantum wave interference applet was started up and detailed questions were asked about whether or not one can know where the photon is and through which slit it goes. Three and nine months later students were able to recall quite a few of the details and most remembered the main features of the conclusions.

Statements from students V and W after 3 months

Two slits, which demos were done? *Quantum suitcase, normal particles, photons. With particles one would expect two stripes and with waves interference. We saw waves.*
There was sound, what did that indicate? .... *particle.*
What else was in the suitcase? *Lens, sun glasses, makes light less bright, this made sure that they went one-by-one. Although it was one-by-one, we saw wave behavior.*
What is interference? *2 waves come together, then are added up and there are minima and maxima, constructive and destructive interference.*
When a photon comes alone .... there is no interference .....but we saw that there was interference.
Other demo's before the suitcase: *there was spraying through a double slit* (spray paint), *those were just particles. We also saw a bath tube with slits* (simulation).
PhET applet: where is the photon? ..... *You do not know that, that is uncertainty, at certain spots the chance was greater, such as in the middle, the probability was the amplitude squared.*
Can you tell through which slit it goes? *No*
At the detector: .... *they will behave like particles*
If you use electrons? *Electrons will also behave like waves.*
Do you get an interference pattern or particle pattern? .... *will probably be interference pattern..*
And if you use a very large molecule like C60 ... *never heard of.*

Why does the interference pattern disappear with large particles? *That has to do with the mass.*

Statements from student X after 9 months (in italics)
On important differences classical versus modern physics: *if you would film something, it would behave differently compared to when you do not film it* [he means when you observe/measure or not]. *That is different* [in classical physics*] with gravity.*
About the experiment: *I remember something with two slits. With particles you get two stripes, with wave behavior an interference pattern.*
Components of the suitcase: *slits, a little plate* [detector] *which observed everything and sent it to the computer, a source, I do not remember whether it was an electron gun or something like that.* [interesting, some students in the interview were not sure whether we had used light or electrons, which may actually be a nice outcome].
The series of demonstrations: *We came to sit here [in this room], I am not sure what we did before or after the demonstration.*
You did not see other 2-slit experiments? *Yes in a YouTube or something.*
What could you see or hear? *Some ticking and a graph. [with his fingers he draws a correct interference pattern in the air].*
That ticking, what was that? *I am not sure, I think it was not often enough for all the points in the graph.*
What was it all about? *I think duality. I think I did it twice, once that we got two stripes and once that we got an interference pattern.*
A wave is from a point and then it expands. Waves can amplify each other. An interference pattern*? That indicates a wave.* Spray paint*: would give two lines.*
In classical physics you expect that they go straight and then you get two lines.
In quantum physics you could have 2 stripes or interference. Two stripes if you would <u>*look*</u> *or something like that.*
What is the change in interference pattern when the particle goes faster or slower? *I do not know whether we learned that or else I forgot.*
The interviewer shows the de Broglie formula and that is a bit familiar.
*Bigger mass, smaller wave length. I do not know what the h stands for [*he forgot the Planck constant!!!!!*]*
Bigger velocity, stripes closer together.
How about the wave length of a basketball? *Very small.*
The PhET simulation, do you know where the photon is? *I think the photon was everywhere, the wave is everywhere.*

Two students Y and Z, a 5-minute interview as they have a class:
What do you remember of the suitcase experiment?
With particles, light maybe, a laser, the light went through 2 slits. There was a detector and a pattern on the screen, that was an interference pattern with the two slits.
One-by-one: *then it will go through one or the other and you get 2 peaks (2 stripes). The other student said: I am not sure.*
Wave-particle duality: *waves produce an interference pattern. Particles should not, but they still produce interference.*
The simulation: *when you do not look for the particle, then it is everywhere, until it hits the screen.*
When wave behavior, when particle behavior? *When you observe you get particle behavior, when you do not look, you get waves.*
If they go one-by-one: One student says *there will be two stripes*, the other says *there will be interference.*

Where with many demonstrations students forget details and conclusions, our efforts in this demonstration to make it memorable succeeded in that over half of the students interviewed could remember important details and conclusions. In these interviews as well as in interviews within weeks after the experiments [6] quite a few students could not connect the de Broglie formula (λ=h/mv) with this experiment while that formula so nicely connects particle properties like momentum with wave properties like wave length. In future demonstrations we will have to better integrate the de Broglie ideas and formula. However, the basic set-up of the demonstration has been validated by the retention results.

References

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