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

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Abstract: 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]. Nevertheless, for secondary school quantum physics we developed a portable double slit demonstration mounted in a suitcase in which photons pass the slits approximately one by one and yet together produce an interference pattern. Based on experiences in 5 schools, we carefully designed the educational aspects of the demonstration and investigated its long-term learning effects through a written test of 68 students after 4 weeks and retention interviews after 4 months (10 interviews) and after 9 months (5 interviews). Students did remember the setup and results of the demonstration quite well. They were quite aware of the unexpected and strange wave-particle behavior of quantum particles in the demonstration including the effect of measurement or observation on the outcomes. However, half of them still had trouble defining duality in their own words and most of them did not remember de Broglie particle waves and how that related to the double slit experiment.

1. Introduction
After many pilot projects since the 1960s quantum physics has finally been incorporated in the mainstream curricula of many countries. Wave-particle duality features in 22 of the 23 countries and states syllabi reviewed by Stadermann [5] as it is one of the core concepts of quantum physics. The double slit experiment provides a nice introduction to duality as Feynman showed in the third volume of the Feynman Lectures. Many authors [6] have discussed conceptual difficulties of students with particle-wave duality and the double slit experiments including insufficient realization of the classic particle-wave difference [7] and reasoning with classical particle trajectories [6, 8]. Experimental results are indisputable, but physics faculty may still differ on interpretations such as whether each photon goes through both slits or through one or whether it is impossible to determine whether a photon goes through one slit or both [8].

Others have developed double slit demonstrations with one-by-one photons for students before. For example, Nuffield Physics in UK in 1970 had an experiment [9] with a flash lamp bulb, several blackened pieces of photo film as filter and a grating. Even at low intensities when photons are far apart, a weak spectrum is still visible. Dimitrova and Weiss [10] created a relatively low-cost set-up with interference of single photons in a Mach-Zehnder interferometer recorded by a storage scope. Rueckner and Peidle [11] constructed a version with a quantum eraser. Modern research versions of the double slit experiment are summarized in Ananthaswamy [12] and Nairz [13]. All of these experiments are...
difficult to implement in secondary schools. We developed a simple, portable, and affordable, demonstration of single photons producing an interference pattern. The demonstration is mounted in a suitcase and can be borrowed by teachers.

Figure 1 shows the set-up of the demonstration. 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 might 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 linearly located along a 1.5 mm interval across 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 and educational description is available from the authors. The demonstration was followed by a teacher presentation and discussion of the PhET-quantum wave interference applet. Please note that since the 1980s double slit experiments with “single” photons are not done anymore with lasers, filters, and slits but with laser pulse induced emission of photon pairs and interferometers instead of slits [12, 13].

![Single photon interference in a suitcase.](image)

2. **Lesson overview**

The following 50-minute lesson took place after several lessons for a very concise treatment of wave optics and introductory lessons on quantum physics including the photo-electric effect and the de Broglie matter waves. Based on earlier experiences and research we decided to optimize the students’ cognitive conflict about particle versus wave behavior with the following series of double slit demonstrations:
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 [14]);
6. “single photon” interference using the experiment described above.
7. A discussion of results using the PhET quantum wave interference simulation [15] to visualize the situation (figure 3).

![Figure 2](image)

**Figure 2** Display of cumulative results of one-by-one photons through the double slit with bin number on the horizontal axis (location in the beam) and counts per bin on the vertical axis.

The demonstrations were led by the teacher but students were asked to individually predict for each demonstration which pattern would be observed on the screen, an image of the slits or an interference pattern. In the single photon demonstration students were also asked to calculate the typical distance between photons with some guidance of the teacher and to construct Excel graphs from raw data rather than having the demo software project them on the screen automatically. Topics for following lessons included amongst others the particle-in-a-box model with some quantitative applications, the Hydrogen atom, the Heisenberg uncertainty principle, and tunneling. The typical number of lessons used for quantum physics is 15 – 18 periods of 50 minutes.

3. **Tests**
68 Students towards the end of grade 11 (age 16-17 in the fifth year of 6 years of secondary education) took part in the demonstration lesson and a written posttest on quantum physics about 1 month after the double slit demonstration. Here we present only results of the double slit 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 larger than 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.

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 an 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.
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. On the other hand, 84% of the students remembered that attempts to find out through which slit the particle would go, would result in collapse of the interference pattern. This could be due to the suitcase experiment or to the dr. Quantum video that was shown. The difference between questions 4 and 5 is probably that students suspect there is a boundary somewhere between classical and quantum particles. In interviews students were not familiar with C60 but they did realize that it should be heavy. We are now preparing a double slit with polarizers to demonstrate the observer effect as well as the quantum eraser.

4. Interviews
22 Students were interviewed on video, 7 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, and 8 of them individually. There were 15 interviews, 10 were 4 months after the demonstration and 5 after 9 months with different students. The questions asked were: a) what is a particle, what is a wave, and what is the difference? what is wave-particle duality? b) remember the suitcase demonstration? What was the equipment and how was it arranged? 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 on its way to the screen. Four and nine months later most students were able to recall most details and most remembered the main observations. Interview results are summarized in Table 1.

Almost all interviewed students remember the main components of the experiment four and even nine months after the experiment. The lens for spreading the beam and the sounds to indicate detected photons are not remembered well but are also not that relevant. Nine out of 15 remember that the set-up can produce a strongly attenuated beam in which photons arrive one-by-one. Two students after 9 months thought that the experiment was done with electrons, we wish that would have been possible in a suitcase! Almost all (12/15) remember that an interference pattern was produced while with particles one would expect two lines as image of a double slit. Most (10/14) also remembered that this would be the case for photons that come one-by-one. Nine out of 15 remembered that trying to detect the photons on their way through the slits would result in two lines and some mentioned this already spontaneously at the start of the interview. This was not demonstrated in the suitcase experiment but told and emphasized after the demonstration while demonstrating the PhET applet. Most (10/14) students had trouble remembering the de Broglie particle waves and recognizing their relevance in this experiment. De Broglie needs to be included more explicitly in future suitcase demonstrations when generalizing from photons to other particles. This also matches with the results on questions 6 and 7 of the written test. Some students had picked up quite well in which situations there is wave behavior (“when you are not looking”) and in which situations there is particle behavior, but others could not point this out in the PhET simulation (figure 4), one duo thought that there was wave behavior in the bright parts (yes) and particle behavior in the dark parts (no).

Statements after 4 months (pair interview Table 1 a, student answers in italics)
Remembering: the quantum suitcase, normal particles, photons. With particles you would expect two stripes and with waves interference. However, we saw waves.
What else was in the suitcase? Lens, sunglasses, to make the light less bright, to make sure that photons went one-by-one.
What is interference? 2 waves come together and they are added and then we get minima and maxima, constructive and destructive interference.
If a photon comes alone, ... there should not be interference, but we saw interference.
PhET applet: where is the photon .... you do not know that, that is uncertainty, at some spots the probability is higher, for example in the middle. The probability was the amplitude square.
Can you tell through which slit it goes? NO
If you put a detector at the slit .... then they will behave as particles.
If you use electrons? Electrons will also behave as waves.
Table 1 Summary of interview answers.

| Topics | 4 months | 9 months | Total |
|--------|----------|----------|-------|
|        | a/Dg     | b/B      | c/Dg  | d/B    | e/B    | f/B    | g/Db   | h/Db   | i/Db   | j/Dg   | k/B    | l/B    | m/G    | n/G    | o/Db   |
| What is duality? | na      | v        | v     | v      | v      | v      | v      | v      | v      | v      | -      | v      | -      | -      | 1/2    |
| Memory of set-up | v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v | v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v | 14/15 |
| lens   | -        | -        | -     | -      | -      | -      | v      | -      | v      | v      | -      | v      | -      | -      | 2.5/15 |
| detector | v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v | v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v/v | 14/15 |
| sounds | v        | -        | v     | v      | v      | v      | v      | v      | v      | v      | -      | -      | -      | -      | 4/15   |
| single photon | v        | -        | v     | v      | v      | v      | v      | v      | v      | v      | -      | na     | -      | -      | 9/15   |

Notes to Table 1: G – girl, B – boy, Dg – Duo girls, Db – Duo boys. A “v” indicates an acceptable answer, “vv” a very good answer, “-” means no answer or a wrong answer, “1/2” refers to an incomplete answer, “na” means not asked. There are a few instances of “v-“, where a pair disagreed with each other, one giving a wrong answer and the other correct. Questions b) and c) were quite easy to code (memory).

Another student pair (Table 1 c):
Suppose the particles come one by one, what will you observe then? I think at the time [of the demo] I thought that interaction [of several particles] was needed to see an interference pattern and that without interaction there would be no interference. .... However, I think that I was wrong and that there actually was an interference pattern. I think at the time I was wrong.
The student started talking with much hesitation, but ended quite convinced that she had been wrong in her prediction then and that there would be an interference pattern when many single photons go one-by-one through the slits [and there was of course]. A example of how cognitive conflict enhanced memory.

Statements after 9 months (single student Table 1 l)
Important differences classical versus modern physics: if you would film something, it would behave differently compared to when you do not film it. 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.
The suitcase: Slits, a little plate which observed everything and sent it to the computer [the detector]: a source, I do not remember whether it was an electron gun or something like that. [this was a good student but he thought the experiment was done with electrons, which would give similar results].
About the series of demonstrations:
We came to sit here [in this room]. I am not sure what we did before or after.
Interviewer: 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 drew a correct interference pattern in the air].
What was it all about? I think duality. I think I did it twice, once that we got two stripes [the paint demo?] 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 look 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 wavelength. I do not know what the h stands for [after 9 months the student forgot the Planck constant!]

Bigger velocity, stripes closer together.

How about the wavelength of a basketball? Very small.

The PhET simulation, do you know where the photon is? I think it was said that the photon was at all places, the wave is everywhere.

Two students after 9 months, (Table 1 o):

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.

And if they go one-by-one (2nd time asked): One student says there will be two stripes, the other says there will be interference.

In two of the 15 interviews (Table 1 i and n) students did not remember much at all. However, they remembered that one would have expected two lines on the screen but that it turned out to be an interference pattern. Most students also had trouble defining the classical distinction between waves and particles, that particles are clearly localized in space and that waves are spread out. But there was also the following answer:

With waves I think of sound and interference and it is everywhere.

Others just mentioned things like waves have a wavelength and frequency, particles have mass and volume, answers which did not have the essence of localization versus spread also found in Johnston et al [16]. The Planck constant was not always remembered in spite of the fact that students had encountered it several times in the photo-electric effect, in the de Broglie formula, and in the Heisenberg uncertainty principle.

![Figure 3 PhET simulation of a photon passing through a double slit.](image)
5. Conclusions

It is surprising that two thirds of the students can still recall so many details of a single lesson out of the hundreds of lessons for many different subjects they had since the demonstration and that these details were not extinguished during summer vacation and the first month of school in grade 12. This shows that with the proper articulation at least some demonstrations can become anchor points for physics experiences and concepts. However, considering the literature on laboratory [1-4] one does have to carefully prepare and integrate demonstrations in the total student experience. The video of Dr. Quantum [14] and the PhET quantum wave simulation [15] did supply valuable complementary input which in our research design we cannot separate from the experience with the suitcase experiment. In future versions of the demonstration and subsequent lessons on quantum physics more attention should be paid to the classic particle-wave difference and to the connection of the double slit experiment with de Broglie matter waves.

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