Research Project Quantum Physics

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Table of Contents

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*QP = Quantum Physics

Introduction

It took me a while before I came up with quantum physics. At first, I hoped it was possible do this project together with a classmate. However, we could not find a topic that interested both of us enough. Actually, after having done a lot of research on the internet, we did find a subject we both liked. It had to do with the Maya's, an ancient Mexican tribe, and their sun-based calendar. What we were interested in mostly, was the physics behind this calendar. Regrettably, we soon had to draw the conclusion that it was impossible to do the project about this. We would get involved in the science of history more than we would be doing calculations. That is, if it was even possible to retrieve the information needed to do these calculations.

So after this attempt to find a suitable subject had failed, we decided to go separate ways, because our interests differed too much. I realized that what fascinates me the most is the theoretical side of physics, so I decided to investigate this option. This is how I eventually thought of quantum physics, though I did not really know what it was. It would take many more hours of research until I had a clear image of what I was up against and even then I was not entirely sure whether it was possible to do some kind of investigation on this subject.

One night during the holidays I was lying in bed thinking about what to do with my project. It was then that I thought of investigating to teach quantum physics in high school. I thought: 'Quantum physics has become such a basic, elementary thing, why are we not learning it in school?' I decided this to be my central topic. However, I did realize that a big part of my investigation would be to explore quantum physics, as I know little of it.

Main Question

Because at the start of my project I did not know a lot about quantum physics yet, it was difficult to set up a detailed main question. That is why I decided to keep it somewhat vague. While doing the investigations I will have to decide what to do specifically, and more importantly what to do not do. Therefore my main question is:

What is the best way to teach quantum physics in high school?

I do know generally in what parts I can divide this main question. A big part of my investigation- I estimate about half of it - will be to do research on quantum physics. Also, the main question can be divided into three parts:

- Which principles of quantum physics need to be taught?
- What is the best way to teach these principles?
- Which educational aspects are important?

These are not real sub questions, though. I will think of specific sub questions once I have done more research. After having done my research on quantum physics, I will probably know generally which principles to teach.

Plan of approach

My research project can actually be divided into two parts. In the first part I will examine quantum physics. I am going to find out what quantum physics is and what its main principles are. Then I am going to write a little piece of text on each of the important elements of quantum physics. This is supposed to be about half of my project. This is a literary research project. I will try to use as many different sources for this as possible. I think, however, that most of these sources will be internet sources. Still I will do my best to find books as well. This part will include at least the following elements:

1. Introduction to quantum physics.
2. The most important principles (wave-particle duality, Heisenberg's uncertainty principle, quantum atom and more).
3. The different (philosophical) interpretations of quantum physics.

The second part I will use to do an investigation on quantum physics myself. My plan is to find out what is the best way to teach quantum physics in high school (vwo-6). Because I do not know a lot about quantum physics yet, I cannot specify this plan any more. I want to do the following (in chronological order):

1. Find out what vwo-6 students are supposed to know already.
   This is also a literature investigation. All the information I need is in the booklet 'Samengevat'.
2. Generally conclude from the literary research which principles absolutely need to be attended to.
3. Find three methods for teaching quantum physics in high school.
4. Use the knowledge I got from the first part of my PWS to compare and judge the three methods. By comparing these methods, I can find out what the possibilities are for teaching quantum physics in high school. Then, by doing interviews, I can find out what parts of these methods are the best.
5. Come up with specific questions about teaching quantum physics in high school.
6. Find answers to this questions by interviewing students, physics teachers and hopefully the authors of the three methods.

Research on QP: what are its most important principles?

Introduction to Quantum Physics

Physics is a means to describe the world around us. It makes use of facts, theories and experiments in order to determine certain physical quantities. Physicists are always looking for knowledge, trying to understand everything. One of the basic physical ideas is that everything *can* be known. To know everything might be difficult. It might even be practically impossible, but theoretically it must be possible. This is the main goal of physics: to know everything.

At least, it has been. For the direction of physics has been changed fundamentally in the 20th century. The world's leading physicists Heisenberg, Bohr, Einstein and many more have developed a completely new kind of physics: quantum physics. Quantum physics is not just another branch of physics, like mechanics or thermodynamics. It *is* physics. Quantum physics is a new way of thinking within physics, that has proven every other theory about anything to be wrong. Da Vinci was wrong, Galileï was wrong, Kepler was wrong and even Newton was wrong. In fact, all physics before quantum physics was wrong.

That is why scientists distinguish two main periods in physics: Classical Physics (also called Newtonian Physics) and Quantum Physics. Classical physicists believed that everything could be known, that every quantity could be determined at any moment in time. This can be done through measurement, or through prediction. This, however, turned out to be wrong in its essence.

According to quantum mechanics, the position of any particle cannot be predicted precisely. The only thing that can be known, is the probability for a particle to be at a certain position. This means - and do not be scared if you do not understand this, because no one really does – that when not measured, a particle is at all positions at the same time, while it is at no position at all. Only when measured, a particle takes a certain position. And even then, not every quantity can be known..

This seems very strange, because it is impossible for us humans to imagine. We observe everything as being where it is. But why should everything we observe be right? Experiments and mathematical theories consistently showed the rightness of this revolutionary quantum theory. Naturally there was a lot of resistance among scientists, when this theory was introduced. Even Einstein did not accept it. But eventually scientists had to accept the facts, and the facts were in favour of quantum physics.

The most important principles

Planck's Constant and light quanta

The founding year of quantum physics runs parallel with the start of the 20th century. In 1900 German physicist Max Planck discovered, that energy is only emitted by blackbodies (a blackbody is an idealized object that absorbs all electromagnetic radiation falling on it.[1]) in discrete packets following the equation

$$E = h f \qquad (1)$$

Where E is energy in Joules, h is the Planck's constant and f is the frequency in Hertz. These discrete packets were called 'light quanta' and later 'photons'.

Planck found this while working on one of the two major problems regarding electromagnetism: the Ultraviolet Catastrophe. Scientists had predicted most of the electromagnetic radiation emitted from a blackbody to be in the ultraviolet region, while the test results showed it was somewhat in the middle of the electromagnetic spectrum. [4]

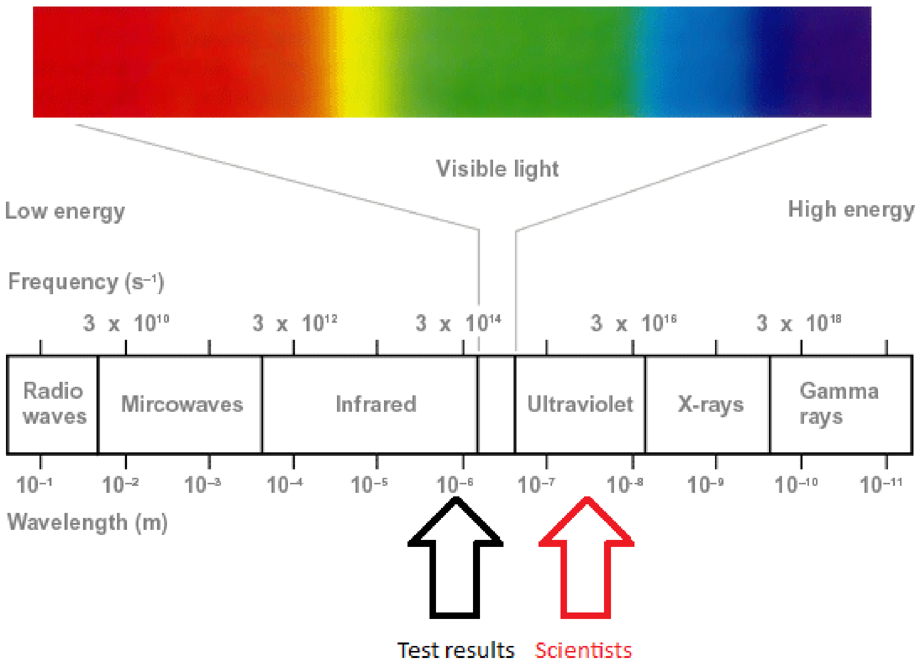

Figure 1: The electromagnetic spectrum[3].

Unlike most physicists at that time, Planck tried to find a theory to fit the results, instead of claiming the results of the experiments were incorrect. That is how he eventually found the 'simple' E = h f equation.

At the time, Planck's idea was radical. Planck's theory was mathematical and although it solved the Ultraviolet Catastrophe, it was not known why light would only be released in these quanta. [2] At first, not even Planck himself believed light was only emitted in these small packets.

Einstein and the Photoelectric Effect

It was Einstein in 1905 who took away the doubt by applying Planck's theory to the second major problem regarding electromagnetism: the problem of the Photoelectric Effect. When light shines on a metal surface, it frees electrons from the metal. This happens because light carries energy and if it has enough energy, it will free electrons. This is called the photoelectric effect.[6] These electrons can be coming out at different velocities and with different amounts, depending on the nature of the light shined upon it.

The problem of the photoelectric effect was the following: if light consisted of continuous waves, which was the commonly accepted theory at that time, an increase in the intensity of the light beam would imply a higher velocity of the beam of electrons. For a higher intensity means the wave contains more energy. This, however, did not turn out to be true. Experiments on the photoelectric effect showed different results (see table).

Results	Higher intensity of light	More electrons, same velocity
Results	Higher frequency of light	Higher velocity of the electrons, same amount
Prediction according to wave theory	Higher intensity of light	Higher velocity of the electrons, same amount
Prediction according to wave theory	Higher frequency of light	No difference at all

When Einstein applied Planck's theory to this problem, he found a solution that matched all test results: light consists of small packets. If light consists of small packets, an increase in the intensity of the light would just mean that more 'light packets' are emitted. Naturally, more emitted light packets imply more freed electrons. Additionally, when the frequency of the light is raised, the number of emitted light quanta, and thus of freed electrons, remains the same. A higher frequency of the light also causes the wavelength to be shorter, which then causes the freed electrons to have more velocity (energy). [5]

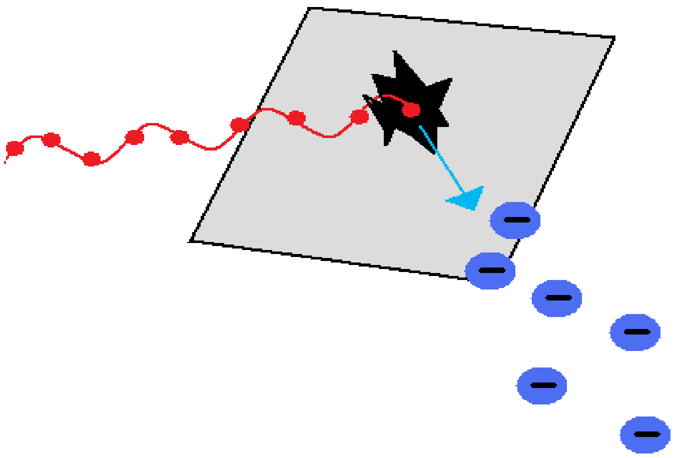

Figure 2: The photoelectric effect. Photons (red) hit the metal (grey) knocking out electrons (blue).

So Einstein showed Planck's theory was multi-applicable, because it had already solved two major scientific problems of that time. From this moment on, physicists began to accepts Planck's revolutionary theory; quantum physics was born.

The Compton Effect

All doubts and uncertainties about the particle nature of light when it interacts with matter were taken away by Arthur Compton. In 1923 he thought of an experiment to confirm the photon (a photon is a discrete light quantum) interpretation of light. This was later called the Compton Effect or the Compton Scattering.

The experiment is very simple: shoot a beam of light at free electrons and measure the quantities of both particles afterwards. This is what classical physics had predicted:

Light (also called electromagnetic radiation)is a wave in the electric and magnetic field. The oscillation of the light wave in the electric field would cause the electron to oscillate as well, and with the same frequency as the incident light ray. Subsequently, the oscillation of the electron would cause electromagnetic radiation to be emitted in all directions – again with the same frequency.[7]

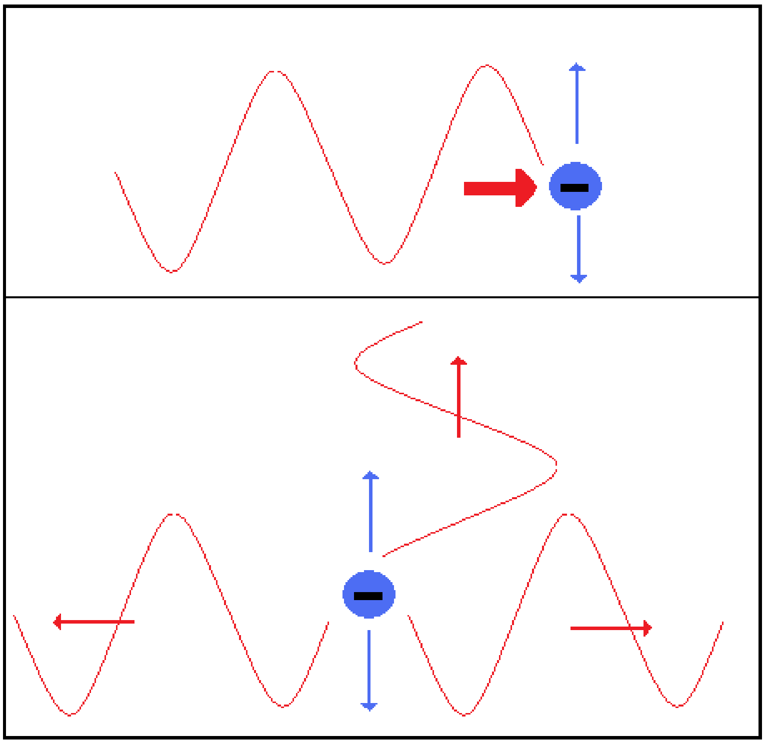

Figure 3: The Classical prediction of the Compton Effect. A (red) electromagnetic wave makes the (blue) electron oscillate (1). The oscillating electron emits electromagnetic radiation in all directions and with the same frequency (2).

This, however, was not what happened. When the electromagnetic wave hit the free electron, it indeed 'bounced off' in many directions. But Compton found that some of the outgoing waves had longer wavelengths than the incoming wave. Therefore, they had a smaller frequency and that is at odds with the (classical) theory!

Just like Einstein, Compton showed that this problem can easily be solved when using the photon interpretation of light. Then the collision would be just like a collision between two particles.

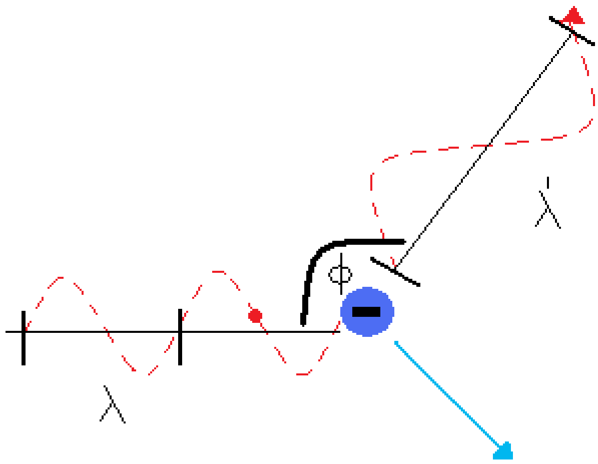

Figure 4: The Compton Effect. A photon (red dot) following a wave-like path (red stripes) hits an electron (blue). The electron starts moving along the blue arrow and the photon bounces off into the red striped direction. Φ is the angle the photon's path makes.

Compton used the photon's properties and the laws of conservation of energy and momentum to derive his Compton Equation:[7]

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\phi) \tag{2}$$

Where λ' is the wavelength of the outgoing photon, λ is the wavelength of the incoming photon, h is Planck's constant, Me is the electron's mass, c is the speed of light and ϕ is the photon's angle. (for the derivation of this equation, see source 7 page 7)

This equation explains the longer wavelength of the scattered photons, for the right-hand side of the equation can never be negative, Because $\frac{h}{m_e c}$ is a positive constant (with a value of 2.4263×10^{-12} m)[7] and cosϕ has a value between -1 and 1. Therefore the difference in wavelengths is never negative, so the wavelength has either increased or remained the same, depending on the photon's angle ϕ.

So once again a major physical problem was solved using quantum physics. Compton's findings seemed to make an end to the discussion about the origin of light. The photon was victorious!

Wave-particle Duality

Light

So light consists of photons: very small light quanta. But what is a photon really? Is it a particle or a wave? Or something in between?

The answer is quite astonishing: light is neither a particle nor a wave, while it is both at the same time. This is called the Wave-particle Duality. When it is not observed, light behaves as a wave. But when it is observed, light behaves as particles. These particles are photons. They are small massless packets of energy. Photons may not have any mass, but they do have momentum, because energy is mass according to Einstein's relativity theory. The equation for a photon's momentum is a combination of the regular equation for momentum p = mv and Einstein's $E=mc^2$:

$$p = E/c \qquad (3)$$

Where p is momentum, E is energy and c is the speed of light.

Derivation

$P = mv = mc$ (photon is light)
$E = mc^2 \longrightarrow m = E/c^2$
$p = cE/c^2 = E/c$

Photons also have a wavelength, though. Combining equations (1) and (3) and $\lambda=c/f$, which goes for every wave moving at the speed of light, an equation can be found for the wavelength of a photon, which depends solely on its momentum.

$$\lambda = h/p \qquad (4)$$

Where λ is the wavelength of the photon, h is Planck's constant and p is the photon's momentum.[9]

Derivation

$$\left.\begin{array}{l} E = hf \\ p = E/c \end{array}\right\} p = hf/c$$

$\lambda = c/f \longrightarrow f = c/\lambda$
$p = (hc/\lambda)/c = h/\lambda \longrightarrow \lambda = h/p$

Young's Double-Slit Experiment

The wave-particle duality can be proven experimentally by doing the double-slit experiment. The double-slit experiment was done in the early 19th century by Thomas Young. [10] He used it to prove that light consisted of waves. What Young did was the following: he first shone light through one slit and measured its intensity on a screen. Then he did the same thing, but he used two slits instead of one. The outcome of the one-slit experiment was in accordance with the wave-theory of light: there was one peek of high intensity in the middle. However, if light was a particle it would make the same image on the screen. The two-slit experiment seemed to confirm the wave-theory of light. For had light been a particle, it would create two peeks of high intensity on the screen. But what happened was that the screen showed an interference pattern, something only found when two waves interfere.

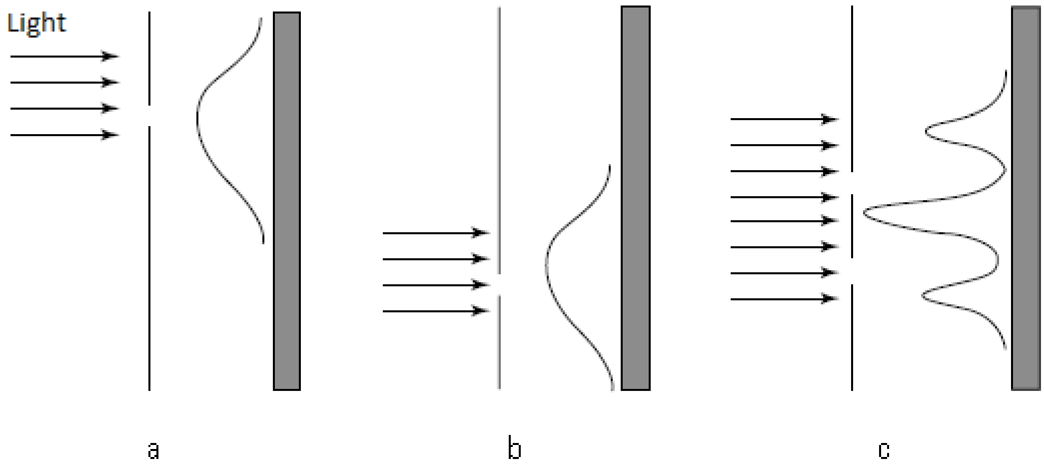

Figure 5: Young's double-slit experiment. [11] The line represents the intensity of the light at that point. At c there is an interference pattern, which occurs when two waves interfere.

In the 20th century, there were new techniques which allowed scientists to fire one photon at a time through the slit. Quite surprisingly, it showed the very same results: the photon, a kind of particle, goes through both slits at the same time and interferes with itself to make the interference pattern. Then, when it reaches the screen it shows up as a particle. Many photons together create the interference pattern. But how can a photon pass through both slits at the same time? That's what scientists thought as well, so they placed a device next to the slits in order to find out which slit it really went through. The result was amazing: as soon as the photon was being observed, it behaved as a particle and the interference pattern disappeared. Instead, just two peeks of high intensity appeared on the screen. [12]

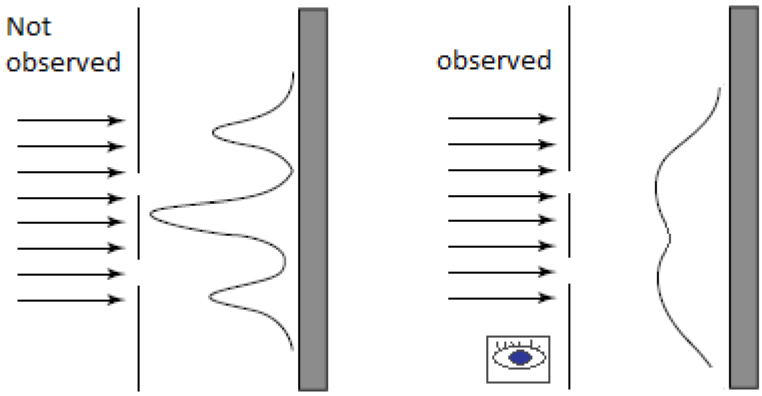

Figure 6: The double-slit experiment when observed and when not observed. [11]

De Broglie's Matter Waves

So light, which was in classical physics defined as a wave, often behaves as a particle. In 1923 Louis de Broglie suggested that the inverse was true as well: matter (particles) can behave like waves.[13] De Broglie based this on mathematical constructs, but it gave a very nice explanation for the energy levels in atoms[9] (see 'The Quantum Atom').

De Broglie thought that the relationship between wavelength and momentum that goes for photons goes for matter as well: $\lambda=h/p$.

If matter and waves were really the same thing, then electrons (particles with mass) would have the same properties as photons. In order to test this, physicists did the same double-slit experiment with electrons instead of photons. The Broglie's expectation was confirmed: when not observed, electrons behaved like waves as well.

In everyday life, we do not notice the wave-like properties of matter, because they are way too small to be noticed at all. Planck's constant has a value of 6.626068×10^{-24} m^2 kg / s. So an object, for example a football, of 0,5 kg moving at 2 m/s would have a wavelength of 6.626068×10^{-24} m. Of course, that's so incredibly small in relation to the football itself that it is too small to be noticed.[9] An electron, however, is significantly smaller than an everyday object (it has a radius of about 2.8×10^{-15} m) and therefore the wavelength is relatively large enough to have a noticeable effect.

Waves of what?

So waves exhibit particle-like properties and particles exhibit wave-like properties. Now you might wonder, waves of what? The answer is not simple, for matter waves are not a physical phenomenon. Matter waves are waves of probability. The probability to find a particle at a certain position is determined by the *wave function* of that particle. When the wave function is squared, you will find the probability of the particle at a certain position.

The wave function is the core of quantum physics. It is a means to describe the state of any particle.[14] Using the very important Schrödinger Equation, which was of course introduced by Erwin Schrödinger, the description of any physical state of a system can be found. The Schrödinger Equation describes the evolvement of the wave-function over time.

Heisenberg's Uncertainty Principle

Another famous fundament of quantum physics is the uncertainty principle. It says that the position and the momentum ánd the energy and time of a particle can never be determined simultaneously. Werner Heisenberg published this idea in 1927.[15]

Heisenberg noticed that in order to define the position of a particle, you (or some measuring device) will have to see the particle.[31] But the definition of seeing something, is that light has to hit the particle. Otherwise it would be invisible. In Classical Physics, the hitting of this particle can theoretically be done as delicate as you like. However, one of the definitions of quantum physics is that there is a limit to this: a photon. So in order to see a particle, it must be hit by a photon first.

Now we want a very accurate measurement of the position of the particle. To do this, we need to hit it with photons that have a very small wavelength, say γ-rays, because photons with a large wavelength would cause a bigger uncertainty in the measurement of the position. But now a problem arises: photons with a small wavelength have a lot of energy ($E=hc/\lambda$). This means the high energy photon will give the particle a relatively big kick, making it impossible to accurately measure the speed (thus momentum, for $p=mv$) of the particle at that same time.[30] A consequence of this is that the position and momentum of a particle can never be measured accurately at the same time; the more accurate the measurement of position, the less accurate the measurement of the momentum and visa versa. This is the core of Heisenberg's uncertainty principle.

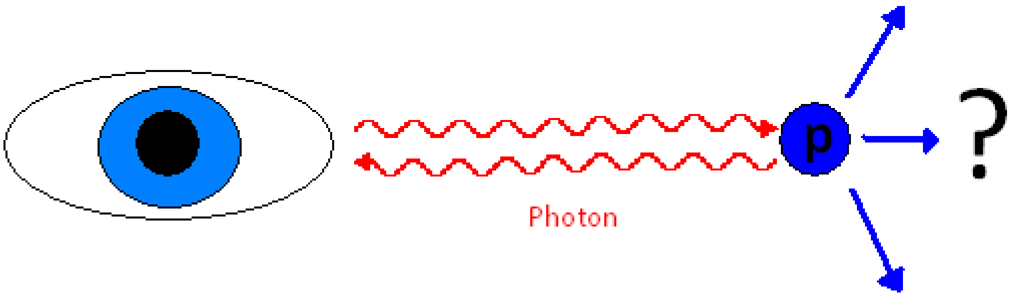

Figure 7. The theory behind Heisenberg's Uncertainty Principle. A photon with a small wavelength hits a particle, giving it a random kick and thus changing the momentum, and the eye observes the reflected photon, seeing the particle's position quite accurate.

Later, the relationship between the uncertainty of momentum and position was found.

$$\Delta p \Delta x \geq \hbar/2 \qquad (5)$$

Where Δp is the uncertainty in momentum, Δx is the uncertainty in position and $\hbar$ is $h/2\pi$.

The same relation also goes for energy and time:

$$\Delta E \Delta t \geq \hbar/2 \qquad (6)$$

At the time, this was a radical idea. It opposed the classical theory that it must be possible to know everything, because Heisenberg had just shown the impossibility of it. Einstein was among the skeptics and he spent a lot of time looking for ways to determine both the momentum and position of a particle at the same time.

The EPR-Paradox

In 1935 he, together with Podolsky and Rosen, invented the EPR thought experiment (EPR for Einstein, Podolsky and Rosen). It works like this. According to quantum physics it is possible to create two identical electrons (i.e. with the same physical quantities): electrons A and B. Anton and Bob have agreed to measure the momentum (Anton of electron A) and position (Bob of electron B) at the same time. Anton and Bob are far away from each other.

So according to the uncertainty principle, the precision of the measurement of the position of electron A determines the precision of the measurement of the momentum of electron B. Because electrons A and B are identical and therefore *entangled*. But, says Einstein, this is at odds with the special relativity theory! Because it means that electrons A and B somehow communicated instantaneously; faster than the speed of light.[17] Einstein refused this idea and called it 'spooky action at a distance'. That's why quantum physics was, according to Einstein, incomplete.

However, there is an explanation for this EPR-paradox. Think of two marbles in a bowl, a black one and a white one. Will and Brian each take a marble out of the bowl, without looking at it, and they run far away from each other. While they have not yet looked at the colour of the marble, both are black nor white. But when Will and Brian look at the marble at the exact same time, Will's marble will turn out to be white and Brian's marble black or the other way around. The marbles didn't communicate, but they were still opposite to each other. That's about the same way it works with electrons and momentum and position.

Measurement and Quantum Physics

The act of measurement comes across many times when speaking of quantum physics. There always seem to be difficulties regarding the measurement of certain values. The double-slit experiment, for example, has a different outcome when it is being observed. This all has to do with the quantization of light.

In Classical Physics, the act of measuring does not affect the outcome of the measurement itself, because the measurement can be done as delicate as you like. In order to measure for example the position of a marble, you (or a measuring device) will have to see the position of that marble. To see the marble, light bouncing off the marble has to enter your eyes. The same goes for a device: in order to measure the marble, light has to hit it first. Of course, the position of the marble will not change after it has been hit by some light. But an electron is much smaller than a marble and therefore it can be affected by the light. But when the amount of light (energy) hitting the electron is made so ridiculously small compared to the electron itself, the impact of it is negligible.

In Quantum Physics, however, this is impossible. Because of the quantization of light, there is a limit to the amount of light hitting the electron: one photon. When the photon hits the electron, it gives it a random kick and thus it changes the electron's position.

So the very act of measurement or observation changes the result of the measurement itself to a certain degree. This is what causes the outcome of the double-slit experiment to change when an observer is added and it is also a fundament for the uncertainty principle.

What happens to the wave function of a particle when it is being observed, is called *wave function collapse.* This is a topic that physicists have been debating on for centuries and that has not yet been resolved (see Quantum Physics and Philosophy: Different Interpretations).

The Quantum Atom

Ever since the discovery of the atom in 1803, scientists have been trying to find out what the atom looks like. There have been several models of the atom. Nonetheless, it was not until 1911 that Ernest Rutherford came up with a model we still use today: the Rutherford Model. Niels Bohr later used quantum physics to improve Rutherford's model and Erwin Schrödinger eventually completed the old quantum picture.

The Rutherford Model

The Rutherford Model is also called the planetary model, because it is very similar to the way planets move around the sun. Although Ernest Rutherford designed his model in 1911, he did not include any quantum physical theories in it. However, it still is a model that is used today, because of the simplicity of it.

Rutherford came up with his model after his famous gold foil experiment. Before Rutherford's model, the leading model of the atom was the 'Plum Pudding model'. It consisted of protons and electrons evenly mixed throughout the atom.

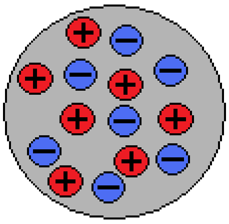

Figure 8. The Plum Pudding model of the nitrogen atom

The gold foil experiment was done as follows. A beam of α-particles (helium nuclei) was fired at a very thin foil of gold. Around this, detectors were placed to detect the α-particles after their collision with the gold foil. The outcome was quite surprising. Most α-particles went straight through the gold foil, some were scattered a little and a few even bounced back 90 - 180°. This scattering at big angles was caused by the 'repulsive Coulomb force', which occurs when the positively charged α-particle collides with another positively charged particle. [18] This positively charged particle had to have a relatively big mass and that is when Rutherford thought of the atom having a positively charged nucleus. [19] Most of the helium nuclei did go straight through, however, and Rutherford concluded the atom had to consist mostly of empty space.

Ernest Rutherford then thought of a model that fit all the experimental data. It consisted of a nucleus consisting of both protons and neutrons, surrounded by electrons. The electrons orbited the nucleus just like planets orbit the sun: in elliptical orbits. The only difference with the planetary model is the kind of force keeping the electron in its orbit: the electrostatic force instead of the gravitational force.

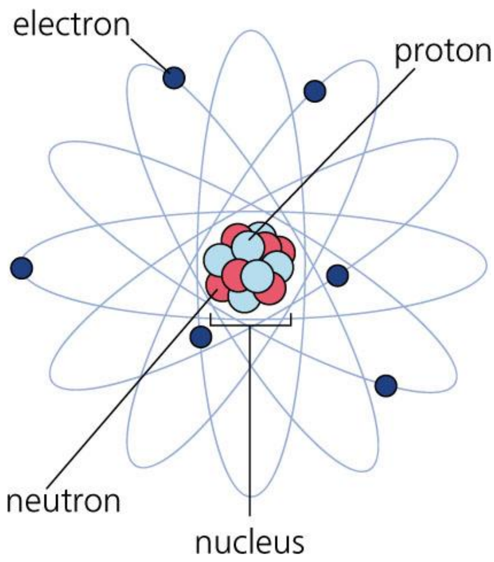

Figure 9. The Rutherford model of the atom.[20]

Bohr's Model of the Atom

Niels Bohr discovered some problems in the Rutherford model of the atom. If electrons orbit the nucleus continuously, then they would have to emit radiation all the time. Since radiation carries energy, this means the electron would keep losing energy. This causes it to be sucked into the nucleus. So that means atoms could not exist! At least, if Rutherford's model was right.

Moreover, if an electron can spiral into the nucleus, it can be at any orbital radius. Because the orbital radius determines the frequency of orbits of the electron around the nucleus, the electron would be able to emit any frequency of electromagnetic radiation. Remember the frequency of the emitted radiation is equal to the electron's frequency. But experiments had shown that a hydrogen atom only emits radiation at certain frequencies. [6]

That is why Bohr decided to apply quantum physics to the atom's model. In 1913, only two years after Rutherford introduced his model, Bohr proposed that the energy of the electrons in an atom is quantized as well. This means electrons can only be at discrete orbits around the nucleus. Other orbits were just not possible. Additionally, the electrons do not give off radiation, unless they jump from one orbit (or energy level, because electrons in higher orbits have more energy) to a lower one. When jumping to a higher energy level, the electrons absorb energy. The amount of this energy is exactly the same as the difference between the energy levels. When an electron in an atom jumps to a higher energy level, the atom gets excited. The lowest possible energy level is called the ground state. [21]

This idea seemed to work out perfectly for the hydrogen atom. It explained very well how the jump of an electron from one energy level to another can emit or absorb energy (or electromagnetic radiation) and Bohr managed to predict the right wavelengths for the emitted radiation of the hydrogen atom and he found the allowed energy levels. Also, Bohr came up with an equation for the angular momentum of the electrons in each ground state.[6]

$$L = n\hbar \tag{7}$$

where L is the angular momentum, n is the quantum number (n=1 corresponds to the ground state, n=2 to the second energy level etc.) and $\hbar = h/2\pi$. (to see how Bohr found this equation, see source 6)

Bohr's model of the atom did have some shortcomings, though. It did not explain why only certain energy levels were allowed. It also did not incorporate De Broglie's matter wave theory, which was of course introduced ten years later. All quantum theory that was introduced later than 1913 was not included in Bohr's model of the atom, so it is only natural that better models would be introduced later on.

Standing Wave Model of the Atom

This is also what happened. Bohr's successful model of the atom was adapted to the new quantum discoveries. When De Broglie discovered his matter waves, he found out this gave a perfect explanation for the existence of energy levels in atoms. Think again of an electron as a wave. The only way it can exist around a nucleus is when at least one wavelength fits around it. One, or two, or three, but never one and half. This gives a beautiful explanation for the existence of discrete energy levels in the atom! It also gives a meaning to the quantum number n: the amount of wavelengths that go around the nucleus.

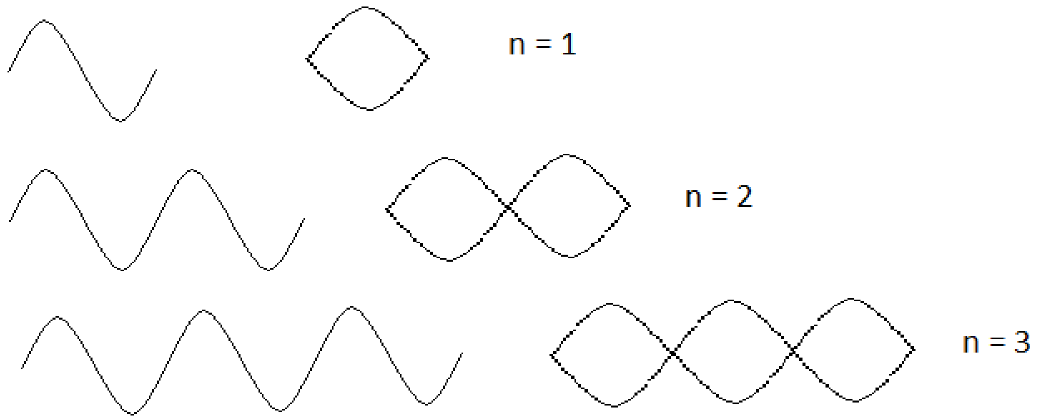

Figure 10. Standing waves. To the left are the amount of wavelengths, to the right the configuration of these wavelengths as they go around the nucleus.

Figure 11.[22] The standing wave model of the atom. Only the 8th energy level is shown. It consists of eight wavelengths.

These waves are standing waves. This means they do not move. Because they are matter waves, they are waves of probability. The electron can be found anywhere within the wave, with a higher probability to be near the nucleus. This model of the atom also explains why the electrons do not give off any electromagnetic radiation when vibrating, because they do not vibrate at all. The electron's wave is stationary, so it does not move. When observed many times, the electron's appearances might show this wave-like path, but it does not mean the electron actually moves. It appears and reappears, but in between that time the electron does not have a definite position.[6] This strange phenomenon is known as quantum superposition.

Pauli’s Exclusion Principle

So we know now how electrons ‘move’ in an atom. But what about the configuration of the electrons among the energy levels? When taking a look at the periodic table, a pattern arises: 2, 8, 18, 32, etcetera. With 2 being the amount of electrons in the inner electron shell, 8 the amount of electrons in the second and so on. There must be a reason why there cannot be more than 2 electrons in the inner shell and 8 in the second. In 1925, Wolfgang Pauli came up with a theory that explains this. It is called Pauli’s Exclusion Principle and it states that no two electrons can occupy the same quantum state.

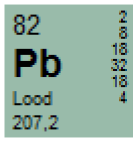

Figure 12: Lead in the periodic table.

A quantum state is described by its four quantum numbers. I will not go into this too deeply, but they each represent a characteristic of that particle, like energy. So for an electron in the first shell, the first quantum number (which is related to the electron’s energy) is 1. Mathematically it is determined that the second quantum number can only consist of an integer between 0 and one less than the first quantum number.

$$N(2) = N(1) - x \quad \text{with} \quad 1 \le x \le N(1)$$

For an electron in the first shell, this means the second quantum number has to be 0. It has also been determined that the third quantum number N(3) can have values between –N(2) and +N(2). In this case, N(3) is 0 as well. This leaves us with only two options, because the fourth quantum number N(4) (which is related to a quantum physical quantity called spin) is either -½ or +½. That is why there can only be two electrons in the first shell.[32]

The same way, the maximum amount of electrons in the second and third shell and further can be calculated. When you carry this out carefully, you will find 8, 18 and 32.

Shell N(1)	1	2	3	4
Max. amount of electrons	2	8	18	32

It does not require an expert to see that the relationship between the shell number (quantum number 1) and the maximum amount of electrons is:

$$\text{Max. amount of electrons} = 2(N(1))^2$$

To generalize, not only electrons obey Pauli’s exclusion principle. Every fermion in a closed quantum system does. Fermions are particles with a half-integer spin. Particles that do not obey the exclusion principle are called bosons; they have whole integer spin. Electrons, protons and neutrons are examples of fermions, while photons are bosons.

Quantum Physics and Philosophy: Different Interpretations

Although quantum physicists are quite sure the mathematical formulations and theories are right, they still struggle to explain them. Quantum physics is a very abstract matter and the mathematics often makes use of imaginary numbers. Also because the results do not seem to refer to our everyday life, it seems nearly impossible to explain quantum physics completely. That is why there are different interpretations of quantum physics, of which the Copenhagen Interpretation and the Many Worlds Interpretation are the most popular among scientists.

> **Definition**
> An interpretation of quantum physics is a set of statements which attempt to explain how quantum physics informs our understanding of nature.[23]

The Bohr-Einstein Debates

In the mid 1920's there has been a revolution in physics. During this period, there were numerous scientific discoveries that led to the foundations of the quantum physics we know now. This caused the physicists' view of the world to change. These new discoveries were the center of a discussion at the Solvay conference in Copenhagen in 1927. The Solvay conference is the world physics conference, where about every three years new developments are discussed. The discussion was between Neils Bohr and Albert Einstein. Bohr argued that the revolution was over and that the quantum theory was complete. Einstein did admit that a lot had been achieved, but he refused the idea the theory was complete. This was the start of many discussions between Bohr and Einstein on the interpretation of quantum physics.

Einstein tried to show the inconsistencies in the theory by 'performing' thought experiments. Note that Einstein did not think the quantum theory was wrong, he was just convinced it was incomplete. One of the thought experiments was the EPR-experiment (see Heisenberg's Uncertainty Principle). Another was 'Einstein's Box'. It was a box Einstein had designed that would be able to measure both the energy and time of an object. Bohr, however, came up with a perfect explanation why it was still impossible to determine both. He showed once again that the uncertainty principle could not be violated. [24]

But Einstein was not convinced that easily. Even in his last published article, he tried to convince the scientific world that the Copenhagen Interpretation of quantum physics was not complete. Even today, many people, including Stephen Hawking, disagree with the Copenhagen Interpretation.

The Copenhagen Interpretation

In 1927 Niels Bohr and Werner Heisenberg expressed their collaborate view on the interpretation of quantum physics during the Solvay conference in Copenhagen. It was the first serious attempt to understand the new quantum physical 'reality'. Although, there was some resistance, most scientists accepted their interpretation. It was later called the 'Copenhagen Interpretation'. The Copenhagen Interpretation consists mostly of the collaborate ideas of Bohr and Heisenberg, but also German physicist Max Born and others contributed to the theory. The Copenhagen Interpretation is not an official theory with clear statements, but it largely comes down to the following principles:

1. Heisenberg's Uncertainty Principle. This means not all quantities of a particle can be known at any time.
2. Bohr's Complementarity Principle, which states that when experimentally shown, matter behaves as either a wave or a particle, but never both at the same time.[25]
3. Born's statistical interpretation of the wave function, which says that the probability of finding a particle at a position is the square of the wave function itself.[24]
4. The Correspondence Principle, which states that for large quantum numbers (large systems) quantum physics approximates classical physics.
5. Wave function collapse. Every process is described by a wave function describing al its possibilities and their probability. However, when observed, the wave function collapses and only describes the event that was measured. This statement is very controversial, because it does not seem to have a physical reality. The wave function collapse has always been a point of discussion among scientists.

Schrödinger's Cat

While Einstein failed to prove inconsistencies in Bohr's and Heisenberg's theory, Schrödinger created a thought experiment showing how odd the Copenhagen Interpretation of quantum physics can be when applied to everyday life. He created what was later called the 'Schrödinger's Cat' thought experiment. It looks like this.

In a sealed box there is a radioactive material which randomly emits photons. There is also a Geiger-Muller counter counting the amount of photons emitted by the radioactive substance. When the Geiger-Muller counter has a value of one, a hammer is released to smash a flask of a very poisonous gas. The released gas immediately kills the cat inside of the box.

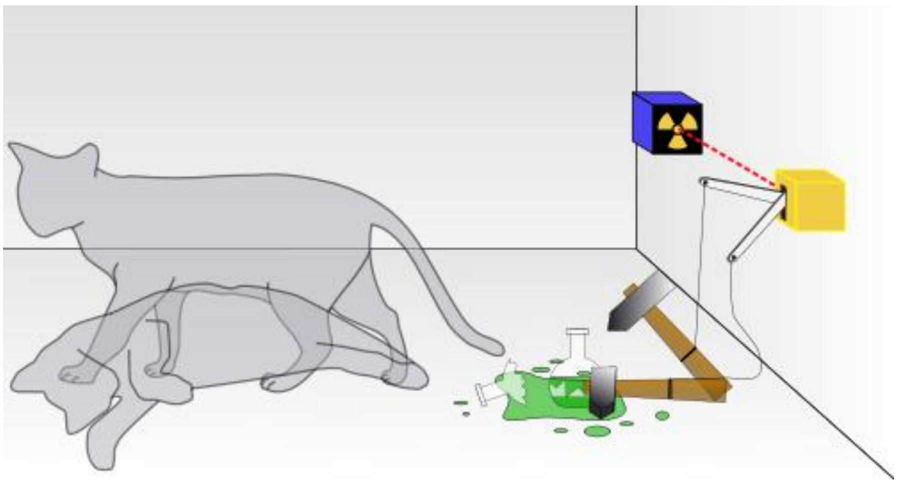

Figure 12. Schrödinger's Cat.[26]

The Copenhagen Interpretation describes the cat as being in a superposition of both dead and alive simultaneously. The wave function gives the possibility of the cat being dead or alive. Only when observed, the wave function collapses and the cat turns out to be either dead or alive. But when not observed, to people outside of the box, the cat is both dead and alive at the same time.

Note that Schrödinger was not seriously considering the possibility of the cat really being dead and alive at the same time. He just designed the thought experiment as a reductio ad absurdum. [27]

The Many Worlds Interpretation

The Many Worlds Interpretations is, next to the Copenhagen Interpretation, one of the most popular interpretations among quantum physicists. Hugh Everett originally formulated the Relative State Interpretation in 1957. Later Bryce Seligman DeWitt made some adaptations and changed the name to Many Worlds.

The main problems the Many Worlds Interpretation solves are the wave function collapse and the randomness, which both play an important role in the Copenhagen Interpretation. MWI states that there is no such thing as wave function collapse or probability. Every possibility occurs, it just does in another 'world' or universe. Therefore it is meaningless to speak about probability. To us, as observers, it appears as if the wave function has collapsed after a measurement has been made. But, thought Everett, what if it has not collapsed at all? Then the wave function would still be continuous, and every possible outcome would exist. Because, according to Everett, the observer and the observed are correlated, it means different worlds exist for every possible outcome. [29] This process is called *decoherence.*

This means that according to MWI there can be infinite worlds. Every quantum experiment has multiple outcomes: one unique one in every world. These different universes cannot communicate with each other. These worlds can be seen as a tree with branches: every time a quantum experiment is performed, a branch splits into more branches. This means, philosophically, that 'our world' has evolved from one of the many parallel histories. Additionally, we are the history of many different futures. [28] Now think about that…

The radical thing Everett did, was that he used the combined wave function of both the observer and the observed, rather than just that of the observed. This makes is possible to think of such different existing worlds.

There are more interpretations of quantum physics which are quite similar to Many Worlds. The difference between these interpretations is mostly in the nature of these different worlds.

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What do vwo-6 students already know?

In order to find out which elements of quantum physics are closest to what VWO-6 students already know, it is evident to find out what these students already know. To do this, I will use the handy booklet ‘Samengevat’ (‘summarized’ in Dutch). In Samengevat, all matter concerning physics that students need to know for their final exam in the Netherlands is summarized. Assuming that quantum physics will be one of the last things they will learn in their last year, this is everything they are supposed to know. Do note that this is only what they are *supposed* to know. It might still be very helpful to revise some of these things in a quantum physics book.

Students are supposed to know the following matter that may be important background information for quantum physics:

- **Waves and vibrations.** Students know what waves are and how they travel. They know about wavelength, frequency, amplitude, the speed of a wave , the energy of a harmonic motion, the interference of waves and what kind of waves there are. They know the formulae $\lambda = v.T$ and $T = 1/f$.
- **Light.** They know about light waves, the interference of light waves, Young’s double-slit experiment, the wavelength and speed of light and the electromagnetic spectrum.
- **Mechanics.** Students know about forward motion, speed, acceleration, forces, Newton’s laws, momentum and circular motion.
- **Work and energy.** They know the formulae for work, for kinetic energy and for weight energy. They also know about power and the law of conservation of energy.
- **Radioactivity.** Students are supposed to know about molecules, atoms, protons, neutrons, electrons, the Rutherford model, different isotopes, α-particles, β-particles and γ-rays. They also know what a Geiger-Müller counter is, how to use Einstein’s $E = mc^2$, and what kind of forces there are in the atom’s nucleus.
- ***Modern Physics.** Students may know a little about photons and their energy, wave-particle duality, Bohr’s atom and energy levels, the emission of photons and the photoelectric effect. However, this part is only tested in the school exam and therefore the student’s knowledge of these things may vary per high school.

General conclusion of literary research: which principles need to be attended to?

Now that I have done a lot of research in quantum physics, I am able to judge its principles. I think that in order for the students to understand the subject, the quantum physical concepts that are taught need to be close to what they know already. This is the only way that quantum physics can be incorporated in the standard high school physics course. Because quantum physics differs so greatly from classical physics and because it often is so abstract, I think the biggest difficulty lies in this part.

What elements of quantum physics are a necessity?

There are a few key concepts of quantum physics that absolutely need to be attended to when teaching quantum physics in high school.

1. **Planck's constant, quantization and the photon.**
   This is the very basis of quantum physics. Without these three elements, there would never have been such phenomenon as quantum physics. It is absolutely essential that students know perfectly well what a photon is and what its characteristics are, because it will come back again and again. Moreover, in order to understand something of quantum physics, they need to know what the quantization of energy is and what this means for physics as a whole. Naturally, Planck's constant, the *factor of quantization*, is part of this as well.
   Besides the necessity, it is also very well possible to teach these elements in high school, because students already know something about it. However, because not every student is at the same level, it has to be explained clearly and elaborate.

2. **Wave-particle duality and Young's double-slit experiment.**
   The question of what light really is has been a subject of debate for centuries. But quantum physics has shone a new light on this discussion. The wave-particle duality is the first theory to match all experimental data. This is also a real key concept of quantum physics, because it follows directly from the theory of the photon. In order to prove the wave-particle duality experimentally, Young's double-slit experiment has got to be used. For students are not satisfied with just theoretical proof, they need physical proof as well. The double-slit experiment shows the wave-particle duality perfectly and at the time it has been very important for the developing of the theory as well.
   It is, moreover, relatively easy to explain the double-slit experiment, because last year high school students are supposed to know it already. This also makes it easier to explain the wave-particle duality of light.

3. **De Broglie's matter waves.**
   De Broglie's matter waves are actually just a logical extension of the wave-particle duality. If waves can behave like matter, why would not matter show wave-like behaviour as well? Because the matter waves are such a logical extension of the wave-particle duality, I do not expect students to have a lot of difficulties with it, even though De Broglie's theory is very abstract. To put things in perspective, I think it is also necessary to explain why we do not

notice this wave-like behaviour in our daily lives. De Broglie's matter waves are not part of the high school physics program at all yet, but students do know a lot about waves. I do want to emphasize that I think it would be a bad idea to get students involved in the probability waves. This is very abstract and far away from the student's knowledge.

4. **The interaction between light and matter and the Photoelectric Effect.**
   In 1905, Einstein's explanation of the photoelectric effect was a major breakthrough. Planck's quantization theory was not yet widely accepted (not even by Max Planck himself) at that time and the photoelectric effect had been a problem for many years. It was from that time on that quantum physics was starting to be discovered. That makes it a very important element of quantum physics. Additionally, the photoelectric effect is a relatively easy subject and students are supposed to know something about it already. It is even possible to do some calculations on it, which is also very important for a physics method. For students are then able to discover the subject themselves and to get familiar with it.

5. **The quantum atom.**
   The last part of quantum physics which is, according to me, an absolute necessity when teaching quantum physics in high school is the quantum atom. Ever since the discovery of the atom, scientists have been trying to figure out what it looks like and what it consists of. Physicists have applied the new quantum theory to the atom and this how they came up with a new theory for the atom itself. It is a necessity, because it is just an essential part of quantum physics and for the understanding of the world around us. Moreover, students know already about electrons, protons and neutrons and the Rutherford model of the atom. The new models of the atom are merely an extension and an improvement of Rutherford's model and therefore it is close to the knowledge the students already have. Besides that, it is a good way to apply the quantization of energy and the matter waves.

Which elements of quantum physics may be suitable as well?

The five concepts of quantum physics that must be explained when teaching quantum physics have been mentioned above. It is important to consider the fact that there is never a lot of space for new physics theory in the high school physics courses. I am experiencing this myself, as I am in VWO-6 at the moment. The physics course is already really full and the speed at which we learn new matter is high. Therefore, there might not be enough space to learn more than just the five necessary elements. This, however, does not mean that other elements are not suitable to be taught in high school at all. Depending on the circumstances, there are other key concepts of quantum physics that could be taught as well.

Heisenberg's Uncertainty Principle
Heisenberg's uncertainty principle is also a key concept of quantum physics. The new theory developed by Werner Heisenberg was very radical at the time, because it opposed the common idea that it must be possible to know everything. It did get widely accepted though, and is nowadays considered as one of the most fundamental aspects of quantum physics. However, the uncertainty principle differs greatly from classical physics. It even is one of the biggest differences between quantum physics and classical physics. This makes Heisenberg's uncertainty principle very interesting,

but also very abstract and extremely difficult, because it is so far away from the students' knowledge. As a result of this, it may not be suitable for high school students. But when explained very delicately and elaborately, it may still be possible to include it in a quantum physics method for high school students. For there is no doubt that the uncertainty principle is a key concept of quantum physics.

Probability and the wave function

These are also very fundamental elements of quantum physics. However, they are very abstract and therefore difficult to comprehend for high school students. The fact that the probability is 'waving', as you could say, and nothing physically is an example of this. As for the wave function, it is very mathematical , but it still might be necessary to mention it.

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Exploring the possibilities: comparison of three existing methods for teaching QP

I have tried to find three methods for teaching quantum physics in high school. However, I only managed to find one. Therefore I tried to look for other sources that could be used to teach quantum physics in high school. That is how I stumbled onto a beginners guide for quantum physics and an interactive website.

Project Modern Physics
The only method for quantum physics for high school students that I managed to find was Project Modern Physics, a Dutch initiative by the University of Utrecht. It is a professional module designed specifically for high school students.

Physics 2000
Physics 2000 is a physics project by the university of Colorado. It is an interactive website which explains modern physics through dialogue. The theory is supported by applets. The website is meant for all ages and tries to emphasize imagery, interactivity and hierarchical organization (source: the Physics 2000 website). This makes it very well suitable for VWO-students.

Quantum Physics – A beginners guide
'Quantum Physics – A beginners guide' is a book written by Alastar I. M. Rae. It is not a book meant specifically for high school students, although students can be seen as beginners. This can be seen in the style of writing and the lay-out. They are novel-like and not schoolbook-like. For example, there are no images and the style of writing is very dry, maybe a little dull

Comparison of the overall content: How do the three methods deal with the five necessary points?

Project Modern Physics, Chapters 2abc and 3a. (http://www.phys.uu.nl/~wwwpmn/)
There is only one chapter of Project Modern Physics that deals with quantum physics. This is, however, the longest chapter and it deals with all five of the necessary points I set out in the previous sub part. The chapter is called, translated from Dutch, 'Photons and Electrons: particles and/or waves?'.

As mentioned before, the chapter deals with all five necessary points. But because there is only one chapter for this, not all points are worked out elaborately. The photoelectric effect, for example, is merely referred to (chapter 2a, 'The photoelectric effect'). There is stated that the photoelectric effect is about the interaction between light and matter and more specifically that it is about light freeing electrons from a metal. That is about it, though. The authors did not point out how Einstein came to his conclusion that light had to consist of quanta.

In contrast to the photoelectric effect ,the wave-particle duality is explained quite elaborate. The entire chapter 2 actually serves the purpose of solving the question whether light is a particle or a wave or both (it is even in the chapter's name). This is done in the same order as it happened in history. Firstly, the authors tell the reader that everyone agreed that light consists of waves (chapter

2a, ‘Licht’). Secondly, they show why light should actually be a particle and finally the conclusion is agreed that light is a not particle nor a wave, but a little of both (chapter 2a, ‘Licht: deeltje én golf?’). Conversely, Young’s double-slit experiment was not described elaborate at all (chapter 2a, ‘Licht’). There was literally one sentence used to describe the entire experiment. *“When light enters a diaphragm with two splits, an interference pattern can be observed behind the diaphragm.”* I think this does not make it clear to the reader what the double-slit experiment really is and how it got so famous.

Because the wave-particle duality is such an important part of the chapter, it is only natural that De Broglie’s matter waves are mentioned as well (chapter 2b, ‘Materie’). I also think the matter waves are mentioned in a logical way: if waves have particle-like properties, why would particles not have wave-like properties as well? The equation for the wavelength of particles is given also. What I think would have improved this part on De Broglie’s matter waves, is when things were put in perspective. For I, as a student, might not understand how matter can behave like waves, because we always see matter as matter and not as waves. Therefore, in my opinion, the explanation would have been more complete when one paragraph had been added about why we do not notice the wave-like properties of matter in every-day life. The authors also tried to explain that matter waves are waves of probability. I found that part a little unclear, however, and it would probably have been better to leave it out.

Furthermore, the photon and the quantization of light are described quite elaborate as well. The photon is a central topic throughout the whole chapter and thus it is described completely. However, it is never mentioned that Max Planck was actually the first to come up with this radical idea of quantization. Mister Planck himself is not even named (chapter 2a, ‘De constant van Planck’), neither are blackbodies or the Ultraviolet Catastrophe. There is one tiny paragraph about Planck’s constant, though, and an experiment to determine it in class.

Lastly, the quantum atom is described in another chapter, called ‘Matter’ (chapter 3a, ‘Atoommodellen’). The first part of this chapter is about the molecules and atoms. The Thomson-model and the Rutherford-model are portrayed in detail, after which Bohr’s model and the later adaptations to the quantum theory are explained as well. This is done quite elaborate, although not enough images are used. I think it would have really helped for the understanding of the students to show an image of the Rutherford-model, for example. Also the concept of standing waves inside an atom needs at least one supporting image, I believe.

What surprises me is that the authors of Project Modern Physics made an attempt to explain Heisenberg’s uncertainty principle (chapter 2c, ‘Onbepaaldheid’). Although they did their best for it by using some images, they did not convince me on this topic. The uncertainty principle is difficult to explain clearly, because it is very abstract. Therefore it is not easy to describe it logically and without any math. The approach with the combination of waves does not seem logical to me when I read it. Personally, I prefer the approach of the random kick given by a photon.

Project Modern Physics also incorporated a chapter about the ‘quantum particle in a box’ (chapter 3b, ‘Het deeltje in een doos’). Even though there might not be enough time available in the vwo-6 physics course, I do think this is an effective way for students to do some calculations on quantum physics.

Physics 2000, The Quantum Atom (http://www.colorado.edu/physics/2000/index.pl)
While Project Modern Physics focuses more on the wave-particle duality, Physics 2000 has the quantum atom as its main topic. This difference in perspective does not mean that Physics 2000 does not incorporate the five key points, though. Each one of them even has a page of itself. Also everything is explained in such a way that it has a purpose for the quantum atom.

The chapter 'The Quantum Atom' starts with the problem of the spectral lines (http://www.colorado.edu/physics/2000/quantumzone/index.html). Atoms emit light, but only some distinct colours. In the 19th century, it was not yet know why this occurred. The authors of Physics 2000 use this problem as an example and an introduction in order to get the student involved. It is an introduction for Bohr's model of the atom, because it was Niels Bohr who came up with a solution for the spectral lines problem. The theory behind Bohr's atom is explained really well and elaborate. It is even possible for the advanced student to get some extra information. There are in total 6 pages reserved for the Bohr-model, whereas Project Modern Physics uses just a few paragraphs for this subject. Of course, this is partly caused by difference in perspective. At the end of the chapter, the Bohr model is extended into the Schrödinger model of the atom, which uses the newest innovations discussed in the chapter up to then to improve the atom's model.

De Broglie's matter waves are dealt with in the page 'Waves & Matter' (http://www.colorado.edu/physics/2000/quantumzone/debroglie.html). What makes it so remarkable, is that they are explained before the wave-particle duality. However, they serve as a reason for the energy levels in Bohr's atom, so that is probably why authors chose to explain this phenomenon even before the wave-particle duality. For the advanced student it is even possible to see the derivation of the formula for the angular momentum of electrons, which follows from De Broglie's theory of matter waves.

Straight after the matter waves, Physics 2000 moves on to the wave-particle duality (same page as De Broglie). This is not explained as elaborately as Bohr's atom, but it is very clear because of the link to Young's double-slit experiment. The double-slit experiment is explained using two pages(http://www.colorado.edu/physics/2000/schroedinger/two-slit2.html and http://www.colorado.edu/physics/2000/schroedinger/two-slit3.html). What I really like are the applets used on this particular topic. They allow the reader to do the double-slit experiment himself, visually. I believe these applets really help the students to understand what they are reading.

Next is the photoelectric effect (http://www.colorado.edu/physics/2000/quantumzone/photoelectric.html). This subject is explained on one page and just as the spectral lines, this problem is used as an introduction for the most important theory: Planck's constant and quanta. I find that the photoelectric effect is described clearly, also because of the use of a supporting image.

What is actually very strange, it that Planck's constant is dealt with at the end of the chapter, while its discovery marked the beginning of quantum physics (http://www.colorado.edu/physics/2000/quantumzone/photoelectric2.html). The theory on Planck's constant is really well integrated though, so the reader does not mind the lack of chronology.

Unlike Project Modern Physics, Physics 2000 does not make an attempt to describe Heisenberg's uncertainty principle. It does not speak of probability waves either.

Quantum Physics – A beginners guide, Chapter 2: Waves and Particles, page 27 – 43 (document on Teletop)

The chapter starts with a number of pages dealing with waves and interference patterns (page 27-33), things VWO-6 students are supposed to know already. One could ask oneself the question, however, whether it would not be handy to revise this (quickly) before beginning about quantum physics. For it is information that is essential for the further understanding of many elements of quantum physics, such as the wave-particle duality.

As the name of the chapter says, the central topic is 'waves and particles', which comes down to 'wave-particle duality'. Therefore, the first thing Rae tries to explain is the wave-particle duality. He does this by first giving information about waves in general, then specifically about light waves (page 33-34) and then of light quanta (page 36-40). Finally he deals with the matter waves as well (page 40-43). In order to explain this duality, the author uses the double-slit experiment, the quantum and the photoelectric effect (in this order).

The double-slit experiment is used as evidence that light consists of waves (page 35). It is explained using clear images to support the text. Because the author has used so much time and space on waves and interference, this is quite easy to follow.

The quantum and Planck's constant are next on the list (page 36 – 40). They serve as evidence for the particle-explanation of light. Rae uses almost one page to describe the Ultraviolet Catastrophe. To me, this part seems both difficult and vague, though. Many assumptions are made in this piece of text, for example that the reader knows exactly what the electromagnetic spectrum is. Besides that, the lack of structure and the use of the same words many times are confusing.

After the quantum, Rae continues with Einstein and the photoelectric effect. The author has not used a lot of space for this topic, so the explanation of the photoelectric effect is not elaborate. Although the explanation itself is clear, it might have been better to use a supporting image as well. For I know what the photoelectric effect is about already, but students might not. Finally, Rae concludes that light has both particle-like and wave-like properties, and that it is a little of both: the wave-particle duality.

The next thing discussed in this chapter are the (page 40 – 43)matter waves of De Broglie. I think they are explained clearly, using the double-slit experiment as proof. What surprised me, is that the author discussed the fact that matter waves are waves of probability as well. What surprised me even more, is that he did it brilliantly. The use of his explanation that nothing is oscillating at all, but that the probability can be calculated using the wave *function*, seems to make this concept a lot easier to understand.

Rae included the 'quantum particle in a box' as well (page 43). However, because of the lack of structure, I did not find this very clear.

In-depth comparison of the literary and educational aspects of one (sub)chapter of the each method

Project Modern Physics, chapter 2a (http://www.phys.uu.nl/~wwwpmn/)
This chapter about light starts with a brief history of the opinions on the origin of light. About light

being either a wave or a particle, ending with a question. I think this is a good way to start, because it makes the student curious.

After this, in the part written in red, Young's double-slit experiment is mentioned. However, this is very brief and it does not give a clear nor elaborate explanation for the interference pattern that is formed. Without any additional information, I do not think a regular VWO-student will understand this part. I think it would probably be better to either leave it out there or explain it more elaborately.

What I do really like are the little experiments that are described in this module. The experiments on the interference pattern really work (I did them myself). I think they give the students a visible proof of what they are reading. This is very important for the understanding of the subject, because it gives the students an image of what they are learning. This helps both to understand and to remember the theory.

Next, the Project mentions two easy examples of phenomena the wave theory of light could not explain. However, the Ultraviolet Catastrophe is not mentioned. The photoelectric effect ís explained, though not very thoroughly. What I noticed is that images are used very seldom. This also goes for the photoelectric effect. Personally, I think images are very important for the understanding of any theory, and especially for quantum physics, because it is such an abstract theory. The text does contain a short piece of text on Planck's constant. However, Max Planck himself is never mentioned, neither are blackbodies. I do think this is essential information for the understanding of the subject. The text does include an experiment to do in class to determine Planck's constant.

The equations for energy and momentum are given, which is a good thing, because it allows the students to calculate a little with quantum physics.

In general, the lay-out looks neat and professional. I specifically like the text squares that indicate which pieces of text contain essential information. This gives the students a better overview of the text and it will help them for studying as well.

Physics 2000: 'The Photoelectric Effect' and 'Planck's Constant and the Energy of a Photon'
http://www.colorado.edu/physics/2000/quantumzone/photoelectric.html
http://www.colorado.edu/physics/2000/quantumzone/photoelectric2.html
The excerpt consists of two subjects: 'The Photoelectric Effect' and 'Planck's Constant and Energy of a Photon'. The Photoelectric Effect is a conversation between teen-aged student Kyla Harrison and Dr. Bob Hellman. I like the way this done, because Kyla represents the student's perspective. Whenever something starts to get unclear, she will ask a question. I am not sure whether VWO-6 students will like it as well, because it may be too childish.

The conversation starts with the student asking Dr Hellman a question. The Doctor then explains clearly what the photoelectric effect is, assisted by a clear image next to him, and asks the student what she thinks. I think this is a very good way to get the student involved, to make the student think actively about the subject. After this, the Doctor is interrupted by Kyla while starting to explain something. This is a perfect example of the benefits of the use of dialogue, because Kyla really acts like an eager student, who will not be satisfied with an unclear answer.

The discussion then leads to the core of the photoelectric effect: the difference between light being a wave or particle. I find that Dr. Hellman explains the theory very clear. However, he sometimes uses a lot of physical phrases like ‘intensity’ and ‘maximum kinetic energy’ that might be difficult for regular students. It might be better to give some extra information here in order to make sure the student follows what you are trying to make clear.

When Kyla asks another question, the Doctor says that he needs to give some more background information first on Planck’s constant and energy quanta. The order of teaching here is non-chronological. The subject starts with the theory of the experiments on the photoelectric effect, which Einstein solved in 1905, and then goes back to Planck’s constant (discovered by Max Planck in 1900) to give more background information. I think this is meant to make the reader curious.

The piece ‘Planck’s Constant and the Energy of a Photon’ starts with the Doc introducing the subject. Planck’s constant is given in bold, and so are some other important words, like ‘photon’. I think this is a good way to show the students what is important. The E=hf relationship is mentioned, but the formula is not shown directly. I think it is really necessary to put this in.

After the photon is introduced, the conversation about the photoelectric effect continues. Using the ‘background information’, Doctor Hellman shows how Einstein came to his prediction. The reader is, however, left with some uncertainty and curiosity at the end, because the discussion about light being a wave or a particle is not really resolved. The Doc does say that light acts sometimes as a wave and sometimes as a particle, but he does not explain why.

Just like Project Modern Physics, the lay-out of Physics 2000 also looks neat and professional. One benefit that makes Physics 2000 unique are the applets that are used. They do not occur in this piece of text on the wave-particle duality, but I do really want to emphasize it. Especially for the double-slit experiment, the applets are very helpful.

Quantum Physics – A beginner’s guide: Chapter ‘Particles and Waves’ page 36-40 ‘Light Quanta’
In contrast to the writers of Physics 2000, Alastar Rae does make use of chronological order. He starts with the discovery of the quantum by Max Planck and continues with Einstein and the photoelectric effect. He eventually ends with a general explanation of light explaining the wave-particle duality.

I do not agree with the title of the book, which states that this is a beginners guide. For the author makes some assumptions (I already mentioned this before) which may not go for every student. However, this is just background information and a VWO-6 student is of course obliged to know some already. It is never a bad thing to revise, though. Still, a more suitable title would be: ‘Quantum Physics – an advanced beginners guide’.

Over all, I think Alastar Rae describes the quantum physical phenomena very well. The explanations are quite elaborate, though not too many difficult details are given. Even though Rae did not use any images, to me it is very clear what he is trying to say. (But is it for students who did not do a lot of research on quantum physics?). The author does use some difficult language, like ‘discrepancy’ and ‘conventional law’, which might be ineffective for high school students. Again, this is due to Rae’s target audience, which probably consists of adults.

There is not a lot of structure in this piece of text. There are no subheadings and there are no white lines. Moreover, Rae did not clearly show the important equations, like E=hf. It is important for students to be able to calculate a little with the theory in order to get familiar with it.

Sources

Universiteit Utrecht, "Project Moderne Natuurkunde", dictaat over moderne natuurkunde voor vwo, http://www.phys.uu.nl/~wwwpmn/

University of Colorado (2000), "Physics 2000", interactive website about modern physics, http://www.colorado.edu/physics/2000/index.pl

Rae, Alastair (2006), "Quantum Physics – A beginner's guide", Oneworld Publications, can be downloaded at TeleTop.

Specific sub questions and interview plan

So now that I have done research on quantum physics and three methods for teaching quantum physics in high school, I am able to define the questions I would like to get an answer to. I want to interview the three groups that are involved with these methods: students, physics teachers and developers of the methods. On the basis of the research and analysis I have done, I aim to find an answer to the following sub questions:

1. Which approach is the best? An approach with the wave-particle duality as its core or an approach with the model of the atom as its core?
   By interviewing authors of Physics 2000 and Project Modern Physics and physics teachers.

2. Is an 'example/problem -theory' approach indeed better than a chronological approach?
   By interviewing physics teachers and Physics 2000 authors.

3. Will it help the students if the relationship between quantum physics and everyday life (micro and macro) is shown?
   By interviewing physics teachers and authors of Project Modern Physics.

4. Do the applets of Physics 2000 help students to understand the theory better?
   By interviewing students and authors of Physics 2000.I want to do two different interviews with students. One interview in which they use the applets of Physics 2000 and one in which they learn about the photoelectric effect normally, without applets. Then I will ask questions to see how well they understood it. This way I can find out whether the applets really work better. Of course, no student can do both interviews, so they cannot influence each other.

5. Does doing experiments help the students to understand the theory better?
   By interviewing students and the authors of Project Modern Physics. I want to do one interview with students after I have shown them some experiments of Project Modern Physics in order to find out what they think of it.

6. Is the use of dialogue in Physics 2000 helpful for the understanding of the theory?
   By interviewing physics teachers and authors Physics 2000.

7. Is it possible to teach Heisenberg's uncertainty principle in high school? If yes, how?
   By interviewing students and physics teachers and Project Modern Physics authors. I want to do two different interviews with students. One for each way of explaining the uncertainty principle. By asking specific questions I can find out which one they understand better (if they understand it at all).Of course, no student can do both interviews.

8. Is it possible to teach about probability and the wave function in high school? If yes, how?
   By interviewing students and physics teachers and Project Modern Physics authors. I want to do two different interviews with students. One to see if the way probability is described in Project Modern Physics works and one to see if the way it is described in Rae's book works. By

asking specific questions I can find out which one they understand better (if they understand it at all). Of course, no student can do both interviews.

I also aim to do every interview with students or physics teachers at least three times. When it turns out to be impossible to interview the authors of Physics 2000 and Project Modern Physics, I am going to try and interview more physics teachers instead and ask them more questions.
The students I am going to interview are vwo-6 students. I will try to interview three students per interview with an average grade of about 6,5 on their vwo-5 report card. This way I can get a good view of the average vwo-6 physics student. Also, before I will let them read their piece of text, I will explain briefly what background information they need to know in advance.

Outline of the interviews with students

Interview #1. To answer sub question 4.
Read Physics 2000 'Young's double-slit experiment'
(http://www.colorado.edu/physics/2000/quantumzone/photoelectric.html)

What does the screen show when waves are shone through two slits? How is that called?
And what does it show when marbles (or bullets) are shot through two slits?
What happens when electrons are shot through two slits one by one?
What do you think of the applets that are used? Are they helpful?

Interview #2. To answer sub question 4.
Read Quantum Physics – A beginner's guide 'Interference' and the first paragraph of 'Matter waves'. (page 34-36 and 40-41)

What does the screen show when waves are shone through two slits? How is that called?
And what does it show when marbles (or bullets) are shot through two slits?
What happens when electrons are shot through two slits one by one?

Interview #3. To answer sub question 5.
Read Project Modern Physics chapter 2a 'Licht' (http://www.phys.uu.nl/~wwwpmn/)

Do you think experiments like this improve your understanding of the theory?
Do they serve as proof for what you have learned?
Do you like doing some experiments once in a while?

Interview #4. To answer sub question 7.
Read Project Modern Physics chapter 2c 'Onbepaaldheid'. (http://www.phys.uu.nl/~wwwpmn/)

Do you know what momentum (impuls) is?
Do you remember which two quantities are complementary? Can you give the equation for this?
When is the position better defined? When many waves are added or when there is only one wave?
Why is the momentum not well defined when the position is well defined?
Why is the position not well defined when the momentum is well defined?

What is the probability of finding a certain momentum?

Interview #5. To answer sub question 7.
Read 'Heisenberg's uncertainty principle' of my research project (page 14)

Do you know what momentum (impuls) is?
Do you remember which two quantities are complementary? Can you give the equation for this?
When is the position better defined? When the wavelength of the incoming photon is big or when it is small?
Why is the position not well defined when the momentum is well defined?
Why is the momentum not well defined when the position is well defined?
What is the difference between a wave and the wave function?

Interview #6. To answer sub question 8.
Read Project Modern Physics chapter 1a 'Waarschijnlijkheid'. (http://www.phys.uu.nl/~wwwpmn/)

What does probability have to do with particles being waves?
When photons hit a photographic plate, does this happen completely random?
Can you predict where a photon is going to hit?
What cán you predict?
What is the chance for a photon to be at a certain position proportional (evenredig) to?

Interview #7. To answer sub question 8.
Read from 'Quantum Physics – A beginner's guide ' 'Matter Waves' (page 40-43)

What does probability have to do with particles being waves?
Is there something waving physically in matter waves?
Can you predict where a photon is going to be when you measure it?
What cán you predict with the wave function?

Outline of the interviews with physics teachers

To answer sub question 1.
Physics 2000 website: http://www.colorado.edu/physics/2000/index.pl see 'The Quantum atom'
Project Modern Physics website: http://www.phys.uu.nl/~wwwpmn/ see chapters 2a, b, c and 3a.
Which approach do you think is the best and why? An approach with the model of the atom as its core (like Physics 2000) or an approach with the wave-particle duality as its core (like Project Modern Physics)?

To answer sub question 2.
Which approach do you think is the best and why? A chronological approach to the theory (so first Planck's constant, then photoelectric effect etc.) or a 'problem-theory approach' (first a problem or example is given and then it is explained using the theory)?

To answer sub question 3.
Do you think it is necessary and helpful to relate quantum physics to everyday life (or micro to macro)? For example by showing experiments or explaining why we do not observe matter as waves.

To answer sub question 6.

Physics 2000 website: http://www.colorado.edu/physics/2000/index.pl See 'The Quantum Atom'.
Do you think the use of dialogue in Physics 2000 is helpful for the understanding of students?
Or do you think a regular approach is better, because it is more structured?

To answer sub question 7.

See Project Modern Physics, chapter 2c, 'Onbepaaldheid' (http://www.phys.uu.nl/~wwwpmn/)and from my PWS 'Heisenberg's uncertainty principle' (page 13).

Do you think it is possible to teach it to VWO-6 students or do you think it differs too much from the regular physics courses? I.e. is it too abstract/difficult to teach to VWO-6 students?
If you do think it is possible: Which way do you think is the best? The way I described it in my PWS (photon giving the particle a random kick) or the way Project Modern Physics describes it (addition of waves)?

To answer sub question 8.

See Quantum Physics – A beginners guide, 'Matter waves' (page 40-43)

Do you think it is possible to teach VWO-6 students about probability and the wave function?
I.e. is it too far away from the regular physics course or can students manage to comprehend it?
If you think it is possible, how would you explain it?

Outline of the interview with the authors of Physics 2000

Why did you choose to use applets to support the theory?
Do you think the applets are a helpful tool for high school students (age ~17) that will help them to understand the theory better? Why do you think so?

Why did you choose to explain the theory using the 'problem-theory approach' (i.e. starting with a problem or an example and explaining it using the theory) ? Do you think this is the best way to teach quantum physics to high school students?

Why did you not choose to explain Heisenberg's uncertainty principle? Do you think it is too difficult to teach to high school students (age ~17)?

Why did you choose to use the quantum atom as the core of the quantum theory? What makes it better suitable than the wave-particle duality, which is the core in educational physics books most of the time? Which approach do you think is best for high school students (age ~17)?

Why did you choose to use dialogue as a means of communication to the students? Is it better than a regular approach? Which approach do you think is best for high school students (age ~17)?

Outline of the interview with the authors of Project Modern Physics

You have incorporated a lot of experiments in Project Modern Physics. Why did you choose to do so? Do you think experiments help students to understand the theory? Why?

The main topic of chapter two is the wave-particle duality and the models of the atom are shortly described in chapter 3a. Why did you choose to make this division? Another physics project, Physics 2000, has the quantum atom as its main topic. Why do you think it is better to use the wave-particle duality as the main topic?

In chapter 2c you have explained Heisenberg's uncertainty principle. Why did you choose to incorporate this in the chapter? Do you not think it is too difficult to comprehend for students? Why?

Why did you choose to explain the uncertainty principle using additions of cosines? There is also another explanation. Its main idea is that when a photon hits a particle, it gives it a random kick. Why do you think the explanation you used works better for students?

You have also chosen to explain the concept of probability in quantum physics. Why did you do so? Do you not think it might be too difficult for students to understand such an abstract matter? Why?

Results

Results for sub question 1

Mr Boomsma: "I think the approach with the wave-particle duality as its core is more intriguing. A lot of people know something about this duality and are fascinated with it. Of course, this wave-particle duality is very abstract and that is one of the reasons way I think it is interesting. Maybe for people who are interested in how one can really use quantum physics, the atom-approach is better. I really think it depends on the audience. But an audience that is interested because it wants to understand how nature behaves at the smallest scales (such as me), the wave-particle duality approach is the best."

Mr van den Brand: "I think the first approach (quantum atom) is the best. By the way, that one starts with the two-slit experiment: interference and thus wave-particle duality. The reason I think this, is that it is better not to work too abstractly, but to use more specific examples."

Mr Goldman (director of Physics 2000): "Most people are more comfortable with matter than with waves. The quantum atom also demonstrates wave-particle duality because the wave functions of the Schroedinger picture of the atom are probability waves. The discreteness of energy levels is easier to understand for atoms and has the added bonus that it explains where light (EM radiation) comes from. I think it is harder for people to understand waves as particles (e.g., photons) with energy but without mass."

Mr Hidden about Physics 2000: "In short: it is strong in the visualization of the experiments and the models. But the 'derivation of the theoretical explanation' of the energy levels in the atom by mentioning the model assumptions and proving them mathematically can only be done as attachment in the current vwo, not as an obligatory part. On the other hand questions about dualism remain: what is waving in an electron?"

About PMP: "To return to your question: PMP gives a lot of depth to the principle of dualism which is close to the way it is thought about in physics. That is POSITIVE, but also NEGATIVE. POSITIVE is also the fact that the text was written on a vwo-56 level in which modern physics is explained elaborately and for most people understandable. NEGATIVE is that this treatment of the matter cannot work in the upper classes of vwo for anyone who follows physics. It is too much, it goes too deep and covers too much."

Results for sub question 2

Mr Boomsma: "I think the 'problem-theory approach' is the best. From psychological research it is known that new knowledge is created while building on old knowledge. First this old knowledge has to be activated. A good way to activate this old knowledge is to let people first solve a problem. After this activation, the correct route to the long-term memory is opened up. The new knowledge gets stored in the right place in the brain."

Mr van den Brand: "See my answer to question 1."

Mr Goldman (Physics 2000): "Science is all about solving problems. A variety of pedagogical techniques should be employed to teach quantum physics to high school students. In European high schools quantum physics is a standard part of the curriculum. The US should get with it!"

Mr Hidden: "A chronological approach is mostly interesting as human interest or 'to think with the scientist' and if you are trying to stimulate skills on the terrain of logical thinking, reasoning and math. Also when you want to emphasize that theory in general and specifically physics is always developing. Already very quickly physics enters the atmosphere of 'doing exercises and solving problems. The latter is not very stimulting for intelligent students, it feels more like a tric. Sometimes that's satisfying (high grades), but learning to explain consequently is eventually for both teacher and student a staying and thus better skill.

Modern physics is very suitable for the historical approach, like a cultural process in which the thinking human because of reason gets more power over a complex reality. And that has led to beautiful theories and apparatuses.

On the other hand the aspect of 'thinking with the scientist' must not be frustrating for the student, because it usually is very difficult. The student who is not so good at mathematics and physics prefers a tight model you can think with. Then the order of discoveries does not really matter.

So I would plead for using clear models, with sometimes 'a sharp edge' to learn thinking about it, and this in a loose historical context. Physics 2000 does this quite well. PMP is not consistent enough."

Results for sub question 3

Mr Boomsma: "As new knowledge is build on pre-existing knowledge, I think it is very helpful to relate quantum physics to everyday life. Most people are of course very used to processes in daily life. This experience can be used to build the new knowledge. This way the new knowledge does not seem as abstract."

Mr van den Brand: " You can do this, but it is no goal on itself. You can use examples like: you look through a window, but you see only a partial mirror image. In short, some photons choose to reflect, others don't. This random choice is typical for quantum physics."

Mr Hidden: "Yes, this is necessary, because students do not want extremely difficult theory, without knowing the consequences of it for their environment. Very abstract theory can be approached with fairly easy experiments (thought experiments). On the other hand is modern physics the basis for unbelievably many apparatuses around us. It must be satisfying to know a little how they work. As a matter of fact, I cannot imagine that a thinking human being would not want this.

Results for sub question 4

Mr Goldman (Physics 2000): "We chose to use applets for interactivity. Scientists usually think in terms of virtual experiments (Gedanken experiments, as Einstein called them). Many of these virtual experiments can never be carried out in a laboratory. Also, interactivity holds more interest. Physics becomes a video game."

Students	**Interview #1**	**Interview #2**
Amount of students who showed some understanding of the subject.	3	3
Amount of students who showed good understanding of the subject.	0	2
Amount of students who found the applets helpful.	2	-
Average physics grade.	6	7

Results for sub question 5

To answer question 5	**Interview #3**
Amount of students who thought the experiments improved their understanding.	0
Amount of students who thought the experiments served as proof for what they had learned.	3
Amount of students who liked doing experiments once in a while.	3
Average physics grade.	6.3

Results for sub question 6

Mr Boomsma: “Of course, the dialogue is a very old approach of discussing physics. Galileo already used it. But I do not think it is the best approach. The questions asked are not necessarily the questions a student wants to ask. Indeed because of the structure, I think the regular approach is better. Since the subject is new to the students, structure is very important.”

Mr van den Brand: “I would use a mixture of the two approaches.”

*Mr Hidden: “*Reading the dialogues is interesting and it discusses many questions students might have. From conversations about PMP I know that also there discussions about the philosophical parts need to be performed. Especially when learning new concepts this is important. Inserting the dialogues like this also gives structure to the thinking process of the students about these difficult concepts. Although it might sometimes look childish or simple, most questions go pretty deep. In short: keep looking for methods to have a conceptual discussion (applets, cartoons, debates etc.).

Mr Goldman (Physics 2000): “We chose to use dialogue to make it more accessible for students. But concerning a method for high school, you would probably need more structure. Perhaps you can incorporate some dialogues."

Results for sub question 7

*Mr Boomsma: "*I think it is certainly possible to teach VWO-6 students something about the uncertainty principle. First of all, an analogue from daily life can be used: a photograph of a moving object (of course, as always with analogues, you have to be careful). I think your approach is better suited for VWO-6 students. It uses physical intuition; a student really gets a feeling about what is going on. Addition of waves is the mathematical reason behind the uncertainty principle. I think that way of explaining is too abstract for VWO-6 students. These students are not used to this very mathematical way of doing physics. Therefore, they will not get the subtleties used in the approach that are needed to understand the uncertainty principle."

Mr van den Brand: "I am certain this is possible. If you take a look at http://www.nikhef.nl/~jo/quantum/qm/qm.pdf and then chapters 3 and 4. This is definitely possible to be taught in high school and it will give a good impression."

*Mr Hidden: "*At the moment I don't remember how you approached this indeterminacy in your research project. I am impressed by the way it is done in PMP: especially the comparison between the determined 'foton hits a negative – makes the spot black' and the undetermined 'wave expands in many directions'. And within that the very strong build up of the interference image because more individual photons form a pattern together. That should be possible on vwo-56 level.'

You can discuss the kind of uncertainty of Heisenberg, but for most students it does not make it more understandable. Another kind of indeterminacy, energy and time, is very nice to understanding radioactive decay. The more fundamental (mis)understanding is within the concepts of probability and the wave function which in some way are linked to chances of finding particles here or there."

Students	**Interview #4**	**Interview #5**
Amount of students who showed some understanding.	1	3
Amount of students who showed good understanding.	0	1
Average physics grade	6.7	6.3

Results for sub question 8

Mr Boomsma: "I think it is not a good idea to teach VWO-6 students about the wave function. It is a very abstract and mathematical concept. VWO-6 students have no experience with the abstract reasoning surrounding the wave function. The simplest system that can be described is a particle in a box, but there is no everyday experience with such a system and is therefore very difficult to be used. Of course, it should be mentioned that matter can behave as waves and that these wave are somehow connected to probability. But I do not think that it is a good idea to go very deep. Maybe analogues and animations can be used."

Mr van den Brand: "That is possible as well. You can see it in my dictation."

Mr Hidden: "This interpretation of the wave function is indeed the missing link in Physics 2000. In PMP it is there, but less clear, more uncertain. Anyway, the problem of a good conception of chance to find a particle somewhere, stays related to the thought that because the wave is everywhere, the particle too is everywhere at the same time.

PMP tries to approach this problem at the root, but does not come to a decisive answer (no complete theory, "we agree that both the particle and the wave are conceptually incomplete"). I can imagine that this message seems to a regular vwo-student like "physics is a difficult subject, too much work, not always good grades and at the end they still don't really know it.""

Students	**Interview #6**	**Interview #7**
Amount of students who showed some understanding.	3	1
Amount of students who showed good understanding.	1	0
Average physics grade.	6	6

Conclusion

To question 1: Which approach is the best? An approach with the wave-particle duality as its core or an approach with the model of the atoms as its core?

From the interviews with physics teachers and Mr. Goldman I can conclude that the approach with the quantum atom as its core works the best for students. Actually all respondents agreed on this. Mr. Boomsma said that the approach with the wave-particle as its core is better for an audience that wants to understand how nature behaves. However, students are usually more interested in the practical part, as Mr. Goldman also stresses. Mr. van den Brand agrees with this. He says it is better to work not too abstractly but to use more specific examples. The quantum atom is of course one of these examples. Moreover Mr. Goldman believes that it is harder for people to understand waves as particles. Mr. Hidden thought that explaining the approach of the wave-particle duality as it is done in PMP (wave-particle duality as core) is positive but also negative, referring to the high level of abstractness.

In short, the approach with the model of the atom as its core works better for students, because it is not very abstract and serves as an example.

To question 2: Is an 'example-theory approach' indeed better than a chronological approach?

This question is somewhat related to question one, as Mr. van den Brand makes clear by referring to his answer to question one, because it is also dependant on the audience. A chronological approach is better if you are interested 'to think with the scientist' , as Mr. Hidden explains. However, this can be very abstract and difficult again. Mr. Hidden also mentions that modern physics is very suitable to the historical approach, but that this can be frustrating for the students. Mr. Goldman and Mr. Boomsma both mention the psychological or pedagogical techniques that should be used. The problem theory approach is one of them, according to Mr. Boomsma, because 'it is known that new knowledge is created while building on old knowledge. A good way to activate this knowledge is to let people first solve a problem.'

In short, the problem-theory approach is the best, since it is less abstract and for psychological reasons it is easier to understand the theory this way. However, a 'loose historical context' is possible, as Mr. Hidden states, but only when problems are still used.

To question 3: Will it help the students if the relationship between quantum physics and everyday life (micro and macro) is shown?

All three physics teachers agree that this is helpful. Mr. Boomsma again refers to the concept that new knowledge is built on pre-existing knowledge and Mr. Hidden even thinks it is necessary. He points out that students 'do not want extremely difficult theory without knowing the consequences of it for their environment.' Mr. van den Brand does admit it is helpful to do this, but it should not be a goal on itself. He and Mr. Hidden both mention that this relation to everyday life can be achieved by simple experiments.

In short, it is definitely helpful to relate quantum physics to everyday life.

To question 4:Do the applets of Physics 2000 help students to understand the theory better?

The outcome of this investigation is that the applets have a potential to be very helpful, but they need to be very clear and some were not clear enough. The reason why Mr. Goldman chose to use applets in Physics 2000 is interactivity and he states that 'interactivity holds more interest'. He also says it is helpful for showing virtual experiments. I interviewed six students; three had read about the photoelectric effect in Physics 2000 (so using applets) and the other three had read about it in Quantum Physics – A Beginner's Guide (so without applets). However, the latter showed better understanding of the subject. What I did notice when interviewing the students was that they only remembered the images of the applets and not what was in the text. For example, one applet showed an unclear image, but the right explanation was in the text. All three of them remembered only the image, though, and therefore misunderstood that part. Do note that the average physics grade of the three students who read the beginners guide was one point higher than that of the students who used Physics 2000. Still two out of three students found the applets helpful.

In short, applets can definitely be helpful, but they need to be clear, because the images of the applets are what students remember the best.

To question 5: Does doing experiments help students to understand the theory better?

This question is related to question three. As a matter of fact Mr. Hidden and Mr. van den Brand already gave their opinion on this. They both stated that simple experiments can contribute to relate quantum physics to everyday life. I interviewed three students. All of them agreed that the experiments served as proof of what they had learned (in other words it related the theory to everyday life). Moreover, they all liked doing experiments once in a while. On the other hand neither one of them thought the experiments improved their understanding. Do note that they read only a few little experiments of PMP.

In short, the experiments are helpful for relating quantum physics to everyday life and students like them, but they don't improve their understanding. So it is handy to incorporate some experiments, but don't expect any miracles.

To question 6: Is the use of dialogue in Physics 2000 helpful for the understanding of the theory?

From the interviews I can conclude that the use of dialogue can be helpful. It should not be the main text type though, because it is not structured enough. You can incorporate some dialogues or cartoons or use debates as Mr. Hidden proposed. Mr. Boomsma emphasizes the importance of structure for students who learn a new subject and therefore thinks the dialogue is not the best approach. In contrast, Mr. Hidden likes the dialogues and thinks they are very interesting. However, he would not use it as his main text type, but he says one needs to 'keep looking for methods to have a conceptual discussion'. Mr. van den Brand has the same opinion. He would use a mixture of the same approaches as well. Mr. Goldman thinks the use of the dialogue makes the theory more accessible, but admits that for high school students structure is important as well.

In short, dialogue should not be used as the main text type, but incorporating it can be very helpful.

To question 7: Is it possible to teach Heisenberg's uncertainty principle in high school? If yes, how?

Every physics teacher I interviewed thought it was certainly possible teach about the uncertainty principle. So that is out of the question. The interviews with students showed clearly that students understand the way I explained the uncertainty principle in my research project (the more intuitive way of a photon giving a random kick) better than the way it is explained in PMP (the more mathematical way using the buildup of waves). For the three students who had learned about it the first way showed much more understanding than the other students, of which the average physics grade was even a little higher. Mr. Boomsma thought the same thing, because 'students are not used to this mathematical way of doing physics'. Contrarily Mr. van den Brand referred to a course on quantum physics he wrote himself. This was not for high school students, though, and it was also very mathematical. Mr. Hidden could not remember the way I had approached it in my research project, so he could not give a definite answer.

In short, it is definitely possible to teach about the uncertainty principle to high school students, but not every approach works the best. Students understand the 'photon giving particle a random kick' way of dealing with the uncertainty principle best.

To question 8: Is it possible to teach about probability and the wave function in high school?

I can conclude that it is possible to teach about probability, but not about what this has to do with the wave function. In answer to question 7 Mr. Hidden already praised the way it is described in PMP and he turns out to be right. After just reading it once all three students showed some understanding of the subject while one even had a good understanding. By using this example of a photon hitting a negative PMP avoids having to explain the wave function. In Quantum Physics – A Beginners Guide and attempt is made to explain the wave function, but this did not lead to a better understanding of the students (only one of three showed some understanding). Mr. van den Brand thinks it is both possible, again referring to his course. It is very abstract and mathematical, though, and I have already concluded in the questions before that this does not work well for students. Mr. Hidden emphasizes that there must be a complete answer. Otherwise students will not be satisfied.

In short, it is possible to teach about probability, but not about the wave function. PMP is a great example of how this can be done properly.

Overall conclusion

As an overall conclusion, I think I can give a pretty good general outline of a method for teaching quantum physics in high school. In 'General conclusion of literary research: which principles need to be attended to?' I already pointed out five aspects that need to be treated. To this, Heisenberg's uncertainty principle and the concept of probability can be added, albeit that the uncertainty principle can best be explained in the 'photon giving particle a random kick' way and probability by avoiding the wave function. Also, it is best to use the model of the atom as the core and a 'problem-theory approach', possibly in a loose historical context, is ideal. The text type should be normal, but inserting dialogues some way (debate or cartoon for example) is important too. Lastly, in order to relate quantum physics to everyday life - a connection students really need - experiments and applets are handy tools.

Error analysis

To be honest, I am quite satisfied with the results and the final conclusions I could draw. I managed to create a general outline of a method for quantum physics, something I had hoped and aimed for. Moreover, it was not very hard to draw these conclusions, because the physics teachers, and Mr. Goldman, mostly agreed. You can imagine how difficult it would have been to draw clear conclusions when all of them had very different. The same goes for the interviews with students in sub questions 4, 5, 7 and 8.

This all has to do with the error analysis. Mr. Goldman, who I interviewed for sub questions 1, 2, 4 and 6, was the only developer of a method for quantum physics I managed to interview. This means that the opinions of the other developers, which probably differ from Mr. Goldman on some subjects because the methods differ as well, have not been taken into account. I did not even plan to interview Alastair Rae (author of 'Quantum Physics – A Beginner's guide'), because I could not find his e-mail address or phone number. I did plan to interview an author of Project Modern Physics, though, but one did not answer my mail and the other I e-mailed was abroad. I had hoped to get an answer from one of them to sub questions 1, 3, 5, 7 and 8. Furthermore, I do not think it would have made any difference when I had any difference when I had interviewed more developers of the same method, because they would be very likely to have the same opinion anyway. So my conclusion to the above sub questions would have been more accurate when I had interviewed developers of different methods for quantum physics.

I have interviewed a total of three physics teachers to answer sub questions 1, 2, 3, 6, 7 and 8. One small problem lies in the fact that Mr. van den Brand is not a real physics teacher, but a professor in subatomic physics at the Free University. This does mean he knows a lot more about quantum physics than normal physics teachers, but he might know less about high school students. This could cause some inaccuracy. Furthermore, the results would have been more precise when I had interviewed more physics teachers.

When analyzing the errors in the interviews with students, there are two factors to take into account: the amount of interviewed students and their average physics grade. I interviewed three students per interview, but often did two different student interviews per sub question (this goes for 4, 7 and 8). For sub question 5 I used one interview, while I did not interview any students for the remaining sub questions. I chose to interview three students per interview, because it was impossible to interview any more at this school. This does mean, however, that the results of the interviews are not very precise. The precision could have been improved by interviewing more students. The students' average physics grade, in contrast to the amount of student, affects the accuracy. Sub question 4 is a good example of this. The difference in average physics grade of the two interviews is one point, and therefore they are difficult to compare. Comparing interviews of students with exactly the same physics grade would have made the results more accurate. For me, however, this was not possible, for the choice of students was so little.

I do think it has been helpful to interview three different groups (students, teachers and developers). This way every party involved in such a method participates; it balances the outcome. As a result of this, the results of sub questions 7 and 8 are most reliable, for they include all three parties.

Further research

I may have come to a good conclusion, but that does not mean that this investigation did not raise any new questions for further research. First of all, I have not had the means to perform this investigation very precisely and accurately, so it can still be repeated, improving the aspects discussed in the discussion.

I shall point out the questions that the investigation has raised in me.

- What kind of applets can be used in a method for teaching quantum physics in high school?
  Physics 2000 used some applets, but not all were very effective and of course there are many other applets that can be used.

- Which experiments can be used in a method for teaching quantum physics in high school?
  There have already been some simple experiments invented, but there can always be more/better. Especially when taking the importance of the relationship between quantum physics and everyday life into account.

- Which tools can be useful for relating quantum physics to everyday life?
  I have found out that applets and experiments are useful, so there must be many more creative tools that can help.

- Which ways to incorporate dialogue/ discussion in a method for quantum physics are helpful?
  I have found out that it is helpful to incorporate dialogue in such a method. Mr. Hidden did mention some ways in which this can be done, but it might be a good thing to investigate which ways really work.

Conclusions versus 'Quantumworld'

Quantumworld is a method for Dutch high school students. It is a project of New Physics and it has been published recently on September 1, 2010. Remarkably, Quantumworld is in many ways in accordance with the conclusions of my investigation. In some ways, however it differs from my conclusions.

Firstly, Quantumworld uses the 'problem-theory' or 'example-theory' approach. Really at the start of almost every (sub) chapter, an example, problem or question is given. In the rest of the chapter this is explained using the theory. This is just like the outcome of my investigation! Also, this is sometimes placed in a historical context, as the name of chapter 2.1 (What we thought to know in 1900) illustrates.

Secondly, in Quantumworld, the uncertainty principle is explained as well (page 28). At first this is done in a simple algebraic way, but in a box on the left is then explained in the 'photon giving particle a random kick' way. And this last explanation is again the same as the one that turned out to be the best in my investigation . In this case I also really believe it is necessary that this second, intuitive approach is shown, because the simple algebraic one did not give me a satisfying complete answer.

Furthermore, Quantumworld relates quantum physics to everyday life all the time. There is even a complete chapter for this (Small quanta in a big world). I think this is a very strong point of Quantumworld. It is done in a very clear way and I personally cannot imagine it not being helpful for anyone. The importance of this relationship was one of my conclusions too. Quantumworld also used some handy experiments to make this connection. Applets, however, were not used.

In contrast to my conclusions, Quantumworld did not use the quantum atom or the wave-particle duality as its core; it is a combination of both. I can understand why the authors have done this, since the module covers so much that it is difficult to stick to one of the two.

The authors of Quantumworld did not incorporate any dialogue, to my surprise. I would have expected them to encourage discussions or put in some kind of conversation. This clearly opposes the conclusion of my investigation that dialogues are helpful. Perhaps this is an aspect of Quantumworld that still needs to be improved.

Overall, I think Quantumworld is a pretty good method for teaching quantum physics in high school. It is certainly an improvement of its predecessor Project Modern Physics. I find the strong relationship from micro to macro one of the best aspects of the method. Moreover, it is on most points in accordance with the outcome of my investigation.

Source

Bemmel, van H (2010), Quantumwereld, for project Nieuwe Natuurkunde, a Dutch method for teaching quantum physics in high school.

Reflection

I chose quantum physics as the main subject of my research project, because I was really interested in quantum physics and I wanted to know more about it. I am happy with my choice, because I do not think I would have put so much effort in it if it would not have interested me. Overall I think the research project went quite well. I managed to finish on time even though I broke my arm in the last weekend and the final results were satisfying.

There are however some things I would have done differently, knowing what I know now. For example, I would have started with a more specific plan of what I would have been going to do. My plan was not that specific, because at first I did not know a lot about quantum physics, so I could not really predict what was going to happen. What I think I did well and what I would do next time as well is that I started very early, already in the summer holidays in which I managed to write quite a lot. Otherwise I might not have had enough time.

Another thing I would have done differently is that I would have e-mailed the respondents for my interviews much earlier. Maybe even before I had made a clear outline of the interviews. For now, I received the answers very late and one answer I did not get at all, because the respondent was abroad this last week. Something else that turned out to be a successful action was to inform my tutor before starting with the interviews. This way he could still give me advise and correct me. I think this has really helped me at that point.

Overall I think my tutor did a good job in helping me along the process. At the start of my project he gave me a lot of advice and he showed me some very useful sources, like Physics 2000 and Project Modern Physics. Even though I did not like it at that time, I am glad he corrected me when I was doing something wrong, like when I was handing out the questionnaire to the students. But there are some things he could do better next time. For example the plan of the questionnaire was already on TeleTop, so Mr. Hidden could have advised me not to do this before I had already done it.

Also it might have helped if he had commented on my research plan during the summer holiday already instead of when school began. Luckily I was doing the right thing, but at that time I was not sure about that.

In conclusion I am content with the way my research project has evolved. There are some things I would do differently now. However, at that time I did not know what I do know now. I am also very happy with my tutor. I think he has helped me a lot.

Log

Date	Time	Progress
June 3rd, 2010	1 hour	Brainstorming
June 10th, 2010	1,5 hours	Research
June 30th, 2010	6 hours	Research
July 1st, 2010	3 hours	Research
August 9th, 2010	4 hours	Thought of better main question, filled in file papers 1 and 2 for the new question and made a plan of approach.
August 11th, 2010	4 hours	Wrote 'Introduction to Quantum Physics' and did research for 'Which principles of quantum physics are most important?'. Also wrote first paragraph of it.
August 13th, 2010	3 hours	Wrote 'Planck's constant and light quanta' and 'Einstein and the photoelectric effect'.
August 16th, 2010	1 hour	Research
August 17th, 2010	3 hours	Wrote 'The Compton Effect' and did research.
August 19th, 2010	3 hours	Wrote 'Wave-particle Duality': Light, Double-slit and De Broglie matter waves.
August 22nd, 2010	3 hours	Wrote 'Waves of what?', 'Heisenberg's Uncertainty Principle' and 'Measurement in Quantum Physics.'
August 23rd , 2010	3 hours	Wrote 'The Quantum Atom.'
August 26th, 2010	2 hours	Started 'Quantum Physics and Philosophy: Different Interpretations.' Wrote introduction and Bohr-Einstein Debates.
August 29th, 2010	1,5 hours	Wrote 'The Copenhagen Interpretation'.
August 30th , 2010	1,5 hours	Wrote 'The Many Worlds Interpretation'.
September 2nd, 2010	3 hours	Reviewed and corrected 'Which principles of quantum physics are most important?'
September 8th, 2010	1 hour	Found third module to teach Quantum Physics in high school and extracted one part of each of the three methods to analyze in detail.
September 12th, 2010	1,5 hours	Wrote analysis of 'Project Modern Physics'.
September 13th, 2010	2,5 hours	Wrote analysis of 'Physics 2000' and 'Quantum Physics – A beginners guide'.
September 14th, 2010	0,5 hours	Wrote hypothesis about how to teach quantum physics in high school.
September 15th, 2010	1 hour	Made questionnaire for students.
September 18th, 2010	2,5 hours	Made new plan for second part of my research project and wrote 'Which principles of quantum physics are suitable for teaching and which are a necessity?'.
September 19th, 2010	2,5 hours	Wrote comparison of the overall content of Project Modern Physics and Physics 2000 of 'Find three methods for teaching quantum physics in school and compare their characteristics'.
September 21st, 2010	1,5 hours	Wrote comparison of the overall content of 'Quantum Physics – A beginners guide' and adapted the 'analyses' of

		the three methods so that it fit the title 'In-depth comparison of the literary and educational aspects of one (sub)chapter of the each method'.
September 22nd, 2010	1 hour	Started 'Plan for interviews with students, teachers and authors of the three methods'. Made questions and interviews 1, 2 and 3.
September 23rd, 2010	3,5 hours	Made outline of the interviews with students, physics teachers and the authors of Physics 2000 and Project Modern Physics. Also made a complete table of contents.
September 24th, 2010	1 hour	Wrote an introduction and a piece of text explaining my main question. Also uploaded everything to Teletop.
September 29th, 2010	3 hours	Made frontpage, changed specific research questions, added clear sources in the comparison of the three methods and corrected and perfected the pieces of text.
September 30th, 2010	2 hours	Again added clear sources in the comparison of the three methods and changed the specific research questions and interviews a little. Also added an explanation of the interviews with students. Handed in the first version of my research project.
October 14th, 2010	3 hours	Interviewed 12 students and sent a mail to Physics 2000.
October 19th, 2010	0,5 hours	Sent e-mails with requests for interviews to three physics teachers, Mr Hoekzema (a developer of PMP)and Martin Goldman (a developer of Physics 2000).
October 21st, 2010	2,5 hours	Interviewed the rest of the students.
October 25th, 2010	0,5 hours	Sent e-mail to physicist Leonard Susskind asking him to answer my questions through mail. Also received answer from Mr Boomsma.
October 26th, 2010	2 hours	Put the results of the interviews with students in easy tables and wrote 'Pauli's Exclusion Principle'.
October 27th, 2010	0,5 hours	Sent e-mail with request for interview to Mr van den Brand, a professor in subatomic physics at the VU.
October 28th, 2010	2 hours	Received answer from Mr van den Brand and Mr Goldman. Also organized all answers (also from Mr Boomsma) and put them under the heading 'Results'. Made some corrections in the project as well.

October 29th, 2010	1,5 hours	Structured the entire document. Changed some headings and the order in which I present them and corrected some mistakes.
October 31st, 2010	-	Broke my arm today, so typing goes very slowly. From now on, further texts take about 3 times longer than normal.
November 1, 2010	10 hours	Wrote conclusion, error analysis, further research, conclusions versus 'Quantumworld' and reflection. Also made some minor adjustments, added footnote, changed table of contents and lay-out. My brother typed out some pieces for me, while I read it to him.