QUANTUMPHYSICS.IOP.ORG

quantum physics for undergraduates

Free teaching resources from
the Institute of Physics

Derek Raine
University of Leicester, UK

Who produced this site?

This site was funded and developed by the Institute of Physics, in response to a discussion meeting in 2010 suggesting the need for a novel approach to teaching quantum mechanics at undergraduate level. Animations were developed by Antje Kohnle's group in St Andrews. Full information on key contributors is here.

Derek Raine - *Project Lead*

Dan Browne - *Author*

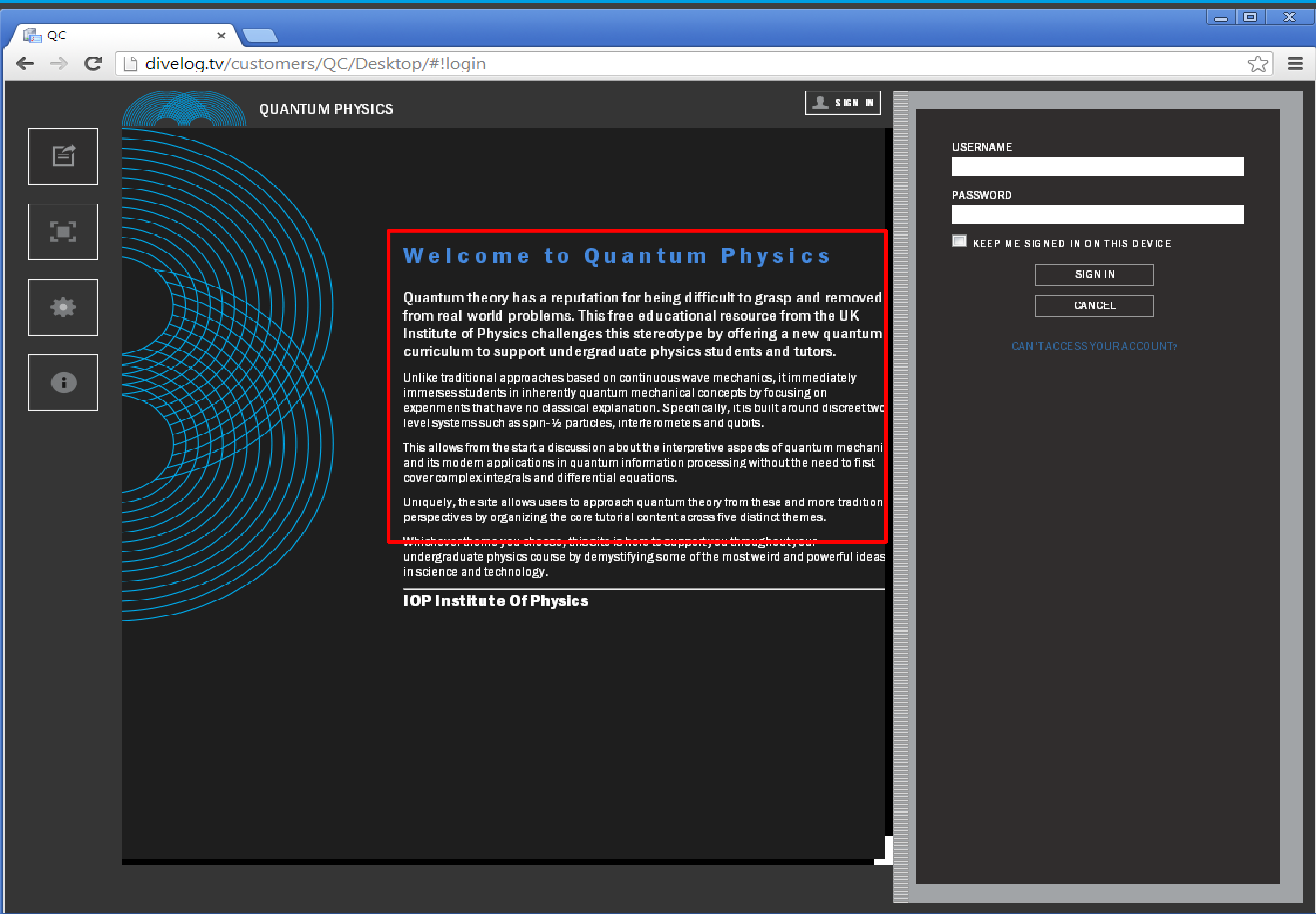
Mark Everitt - *Author*

Pieter Kok - *Author*

Antje Kohnle - *Simulations*

Elizabeth Swinbank - *Editor*

Christina Walker – IOP project manager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Welcome to Quantum Physics
Quantum theory has a reputation for being difficult to grasp and removed from real-world problems. This free educational resource from the UK Institute of Physics challenges this stereotype by offering a new quantum curriculum to support undergraduate physics students and tutors.
Unlike traditional approaches based on continuous wave mechanics, it immediately immerses students in inherently quantum mechanical concepts by focusing on experiments that have no classical explanation. Specifically, it is built around discreet two level systems such as spin-½ particles, interferometers and qubits.
This allows from the start a discussion about the interpretive aspects of quantum mechani and its modern applications in quantum information processing without the need to first cover complex integrals and differential equations.
Uniquely, the site allows users to approach quantum theory from these and more tradition perspectives by organizing the core tutorial content across five distinct themes.
Whichever theme you choose, this site is here to support you throughout your undergraduate physics course by demystifying some of the most weird and powerful ideas in science and technology.
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Uniquely, the site allows users to approach quantum theory from these and more traditional perspectives by organizing the core tutorial content across five distinct themes. Perhaps a historical approach fits best, or you might prefer a more philosophical or mathematical take. Some users will benefit by focusing on experiments or by jumping straight to the most recent applications of the theory. Give each a go, or simply view everything alphabetically

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You may also search for specific text or topics using the tool in the navigation bar, or retake the introductory tutorial at any time during your visit by clicking on the information button on the left.

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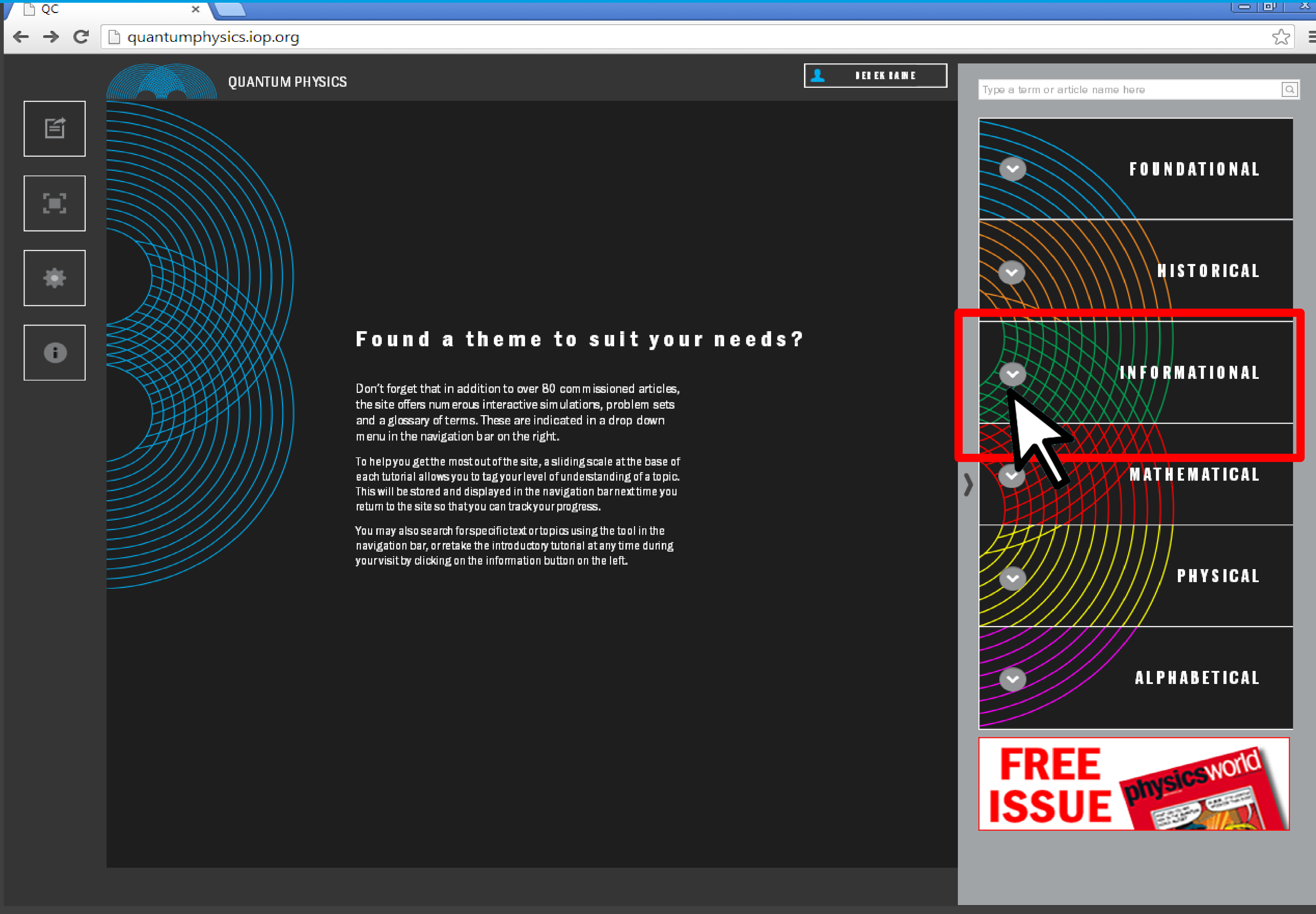
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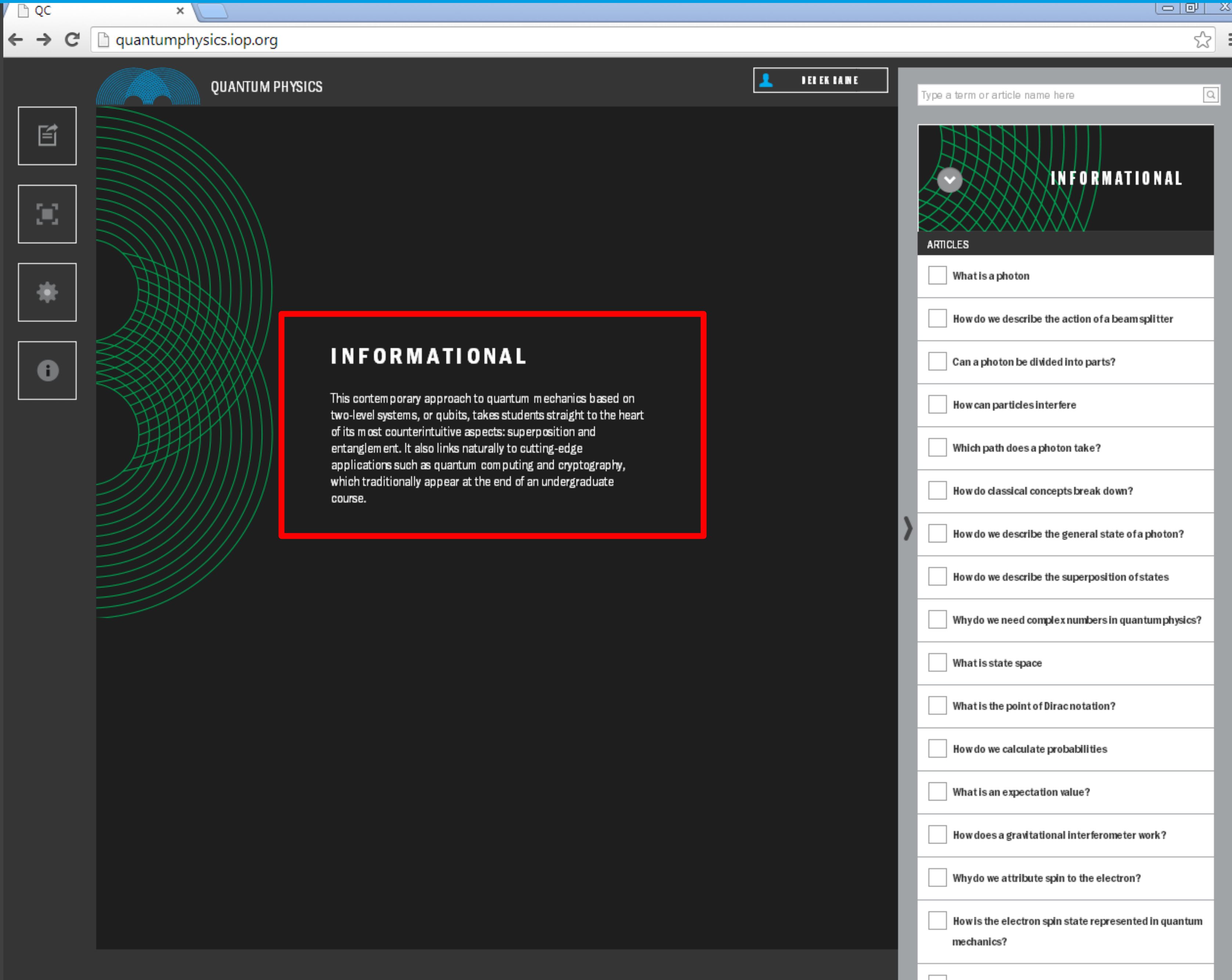
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INFORMATIONAL
This contemporary approach to quantum mechanics based on two-level systems, or qubits, takes students straight to the heart of its most counterintuitive aspects: superposition and entanglement. It also links naturally to cutting-edge applications such as quantum computing and cryptography, which traditionally appear at the end of an undergraduate course.
INFORMATIONAL
ARTICLES
What is a photon
How do we describe the action of a beam splitter
Can a photon be divided into parts?
How can particles interfere
Which path does a photon take?
How do classical concepts break down?
How do we describe the general state of a photon?
How do we describe the superposition of states
Why do we need complex numbers in quantum physics?
What is state space
What is the point of Dirac notation?
How do we calculate probabilities
What is an expectation value?
How does a gravitational interferometer work?
Why do we attribute spin to the electron?
How is the electron spin state represented in quantum mechanics?
What is the magnitude of the electron spin?

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- [ ] Can a photon be divided into parts?
- [ ] How can particles interfere

What is a photon?

Light is an electromagnetic wave, and photons are often described as particles of light or packets of light energy. How can we make this particle description more precise? To begin to answer this question, we will consider a simple experiment in which a laser is pointed at a photodetector (Figure 1). The laser has two settings, high and low, corresponding to high and low output power, respectively.

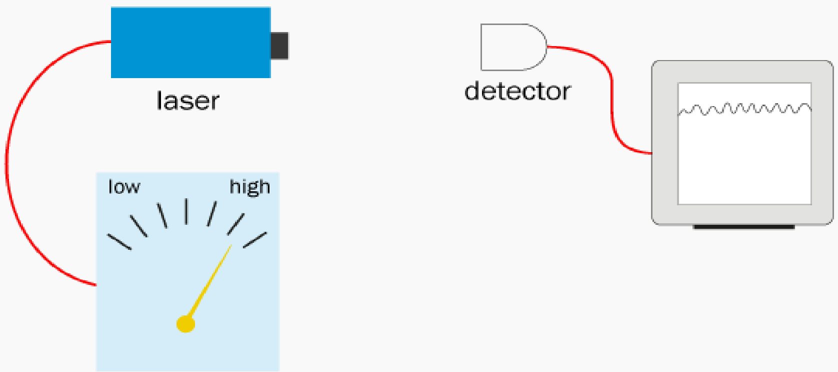

Figure 1: Experiment 1.

Let's say that the high output is about 1.0 mW, which is roughly the intensity of an average (legal) laser pointer. In the photodetector the energy of the light is transferred to electrons, and this generates a current that is read out by an ammeter. When the laser is set to the high power output, we see a steady current on the meter. The size of the current is directly proportional to the intensity of the light.

Next, we reduce the power of the laser by switching the setting to "low". We expect that continuously lowering the power output of the laser will continuously decrease the current in the detector. At first, this is indeed how the system behaves. However, it is an experimental fact that for very low intensities the current is no longer a continuous steady current, but rather comes in pronounced pulses.

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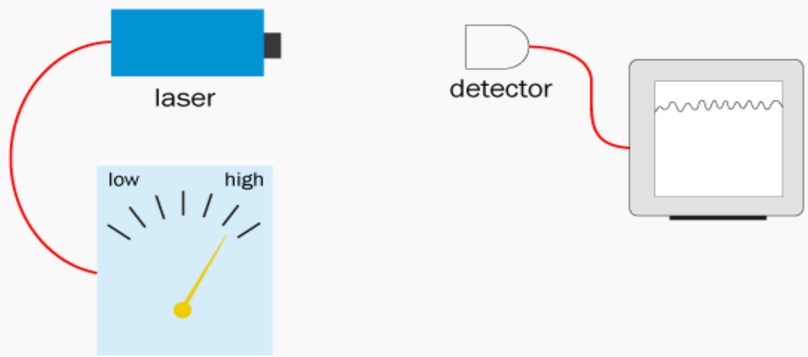

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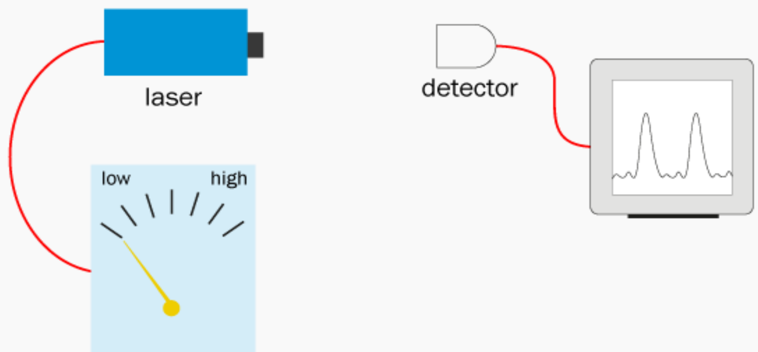

Figure 2: Experiment 2.

This is the first counterintuitive quantum mechanical result. In what follows we will explore the consequences of this fact.

You may have drawn a mental line from the laser to the detector, but there is a reason there is no line in Figure 1. At this stage we do not know what is happening between the laser and the detector; we need to be very careful not to make any assumptions about what happens that does not have an operational meaning in terms of light sources and detectors. You may say, “But I can see the light between the laser and the detector if I blow chalk dust in the beam”, and you would be right. However, the chalk dust and your eye would then become a second detection system that we do not wish to consider at this stage. Having said this, it is customary to interpret the current pulses as small “light packets” travelling from the laser to the detector, shown in Figure 2. These chunks of electromagnetic energy are commonly called photons.

At this stage, then, photons are defined as the cause of the pulses on the ammeter; it is important to remember that we do not really know anything else about these photons. In particular, we should not assume that they behave like objects such as marbles or snooker balls. We need to do more experiments to establish how they behave.

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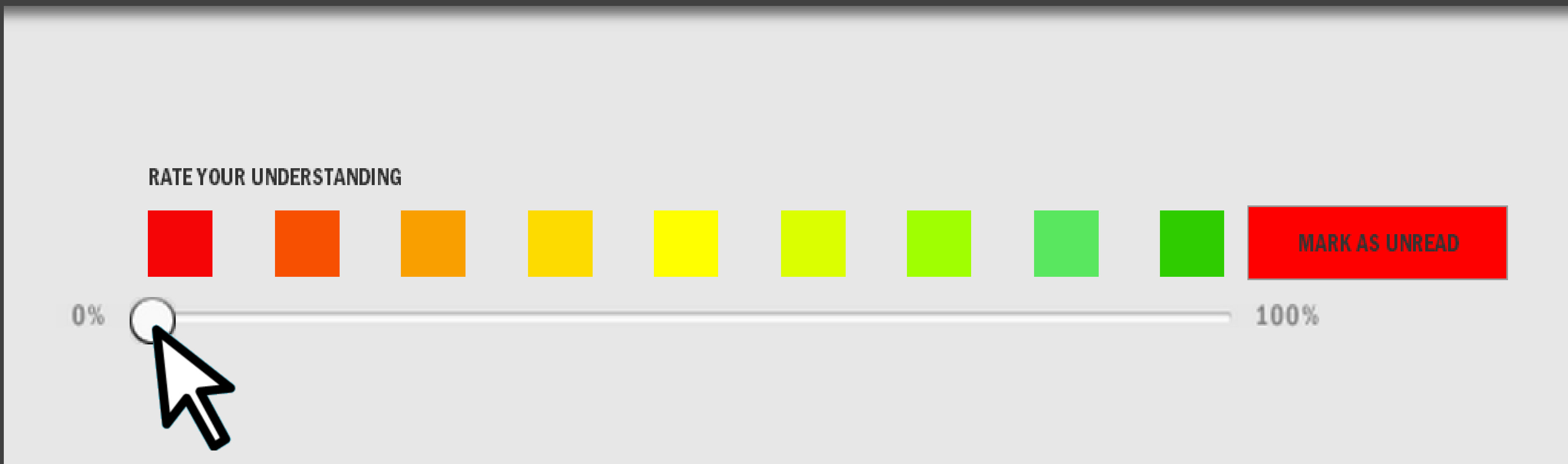
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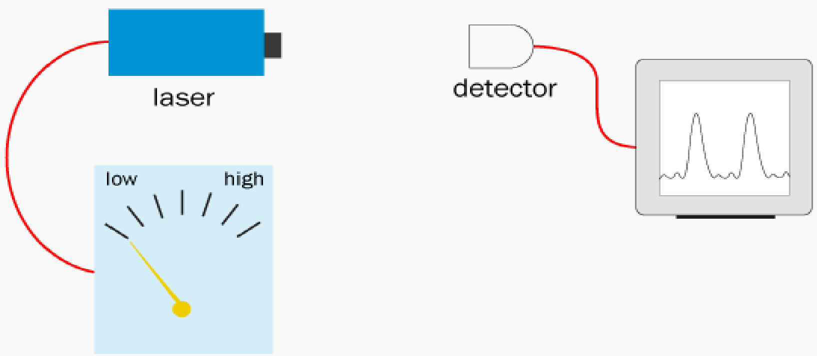

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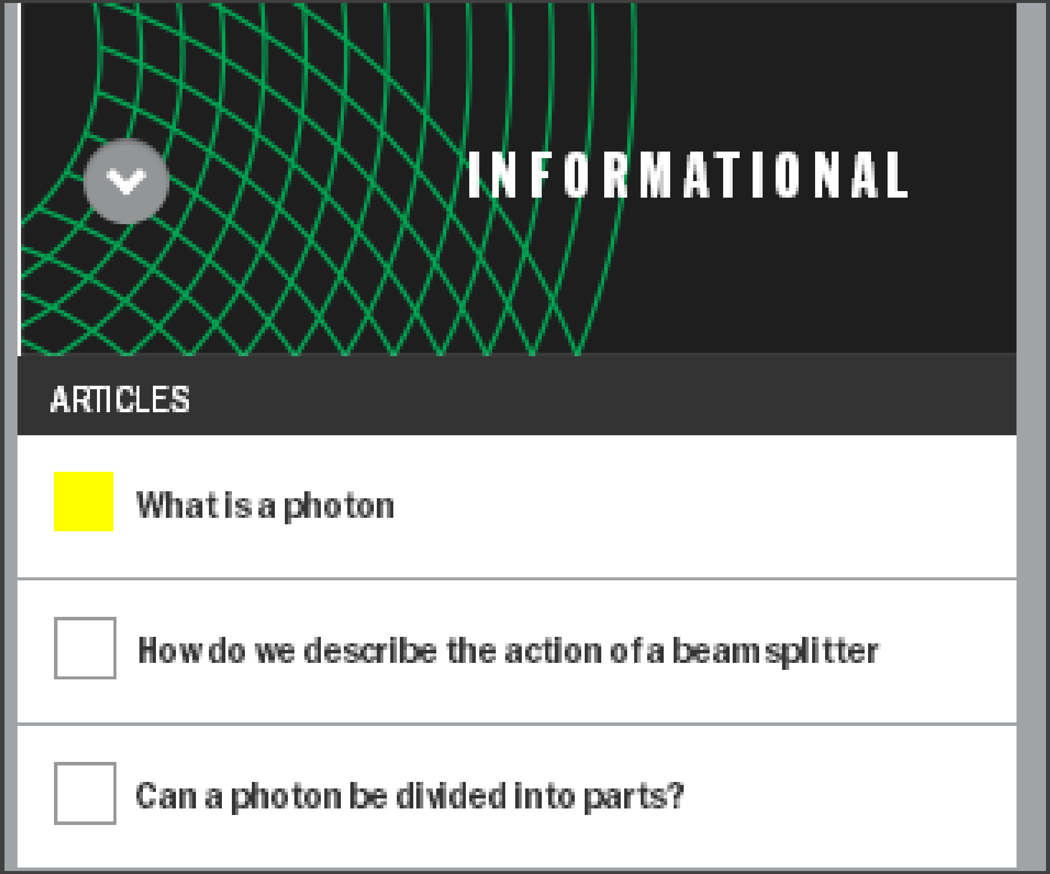

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INFORMATIONAL

ARTICLES

- What is a photon
- How do we describe the action of a beam splitter
- Can a photon be divided into parts?
- How can particles interfere
- Which path does a photon take?

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quantumphysics.iop.org/#!article/interference

QUANTUM PHYSICS

PRE-READ IS AVAILABLE FOR THIS ARTICLE

How can particles interfere?

The simulation **Interferometer experiments with photons**, **particles** and **waves** shows an interferometer similar to the one in the text. Note that the interferometers differ in orientation but the essential physics is the same.

We have seen (**Can a photon be divided into parts?**) that light is made up of photons that have particle-like properties. But we also know that light exhibits interference that is wave-like. How can we describe the interference of light in terms of particles? To answer this question, we do another experiment.

We replace the detectors in our previous experiment (**Can a photon be divided into parts?**) with mirrors and recombine the two beams using a second beam splitter. The outgoing beams of this second beam splitter are again monitored by detectors. The setup is shown in Figure 1.

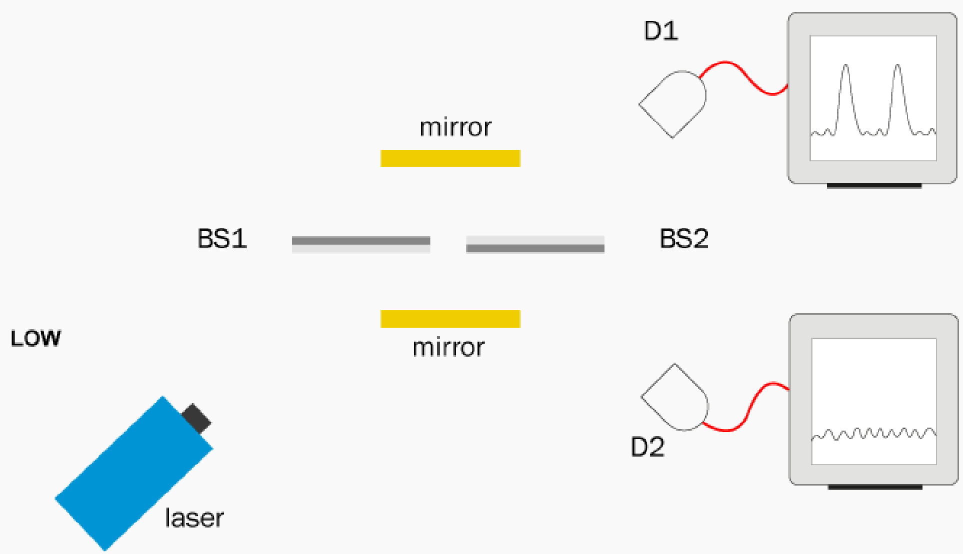

Figure 1: Experiment 5.

Articles have suggested pre-requisites

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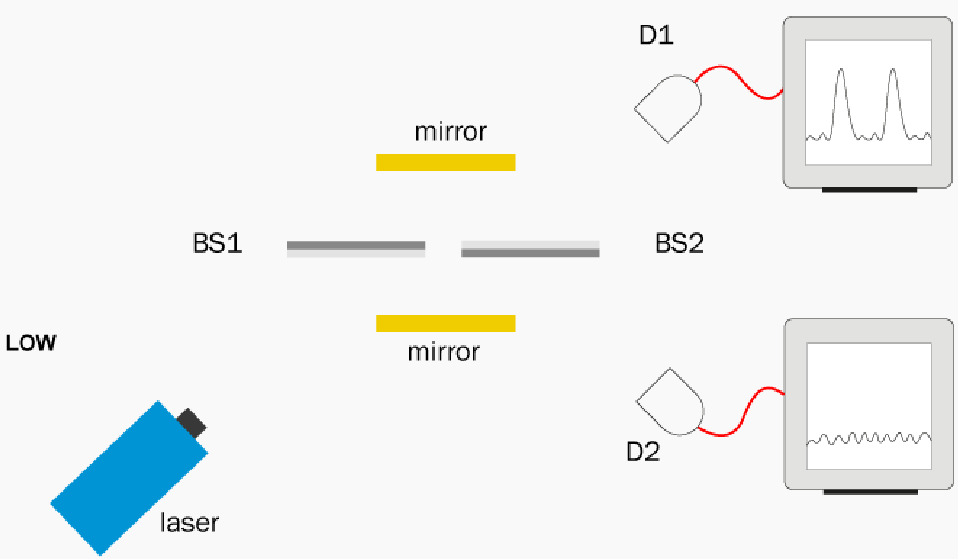

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Articles are hyperlinked

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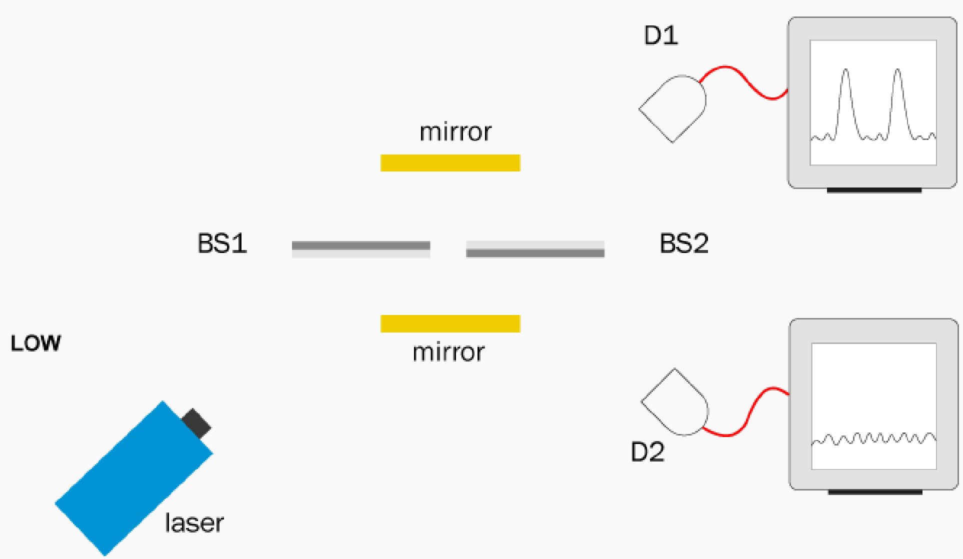

Figure 1: Experiment 5.

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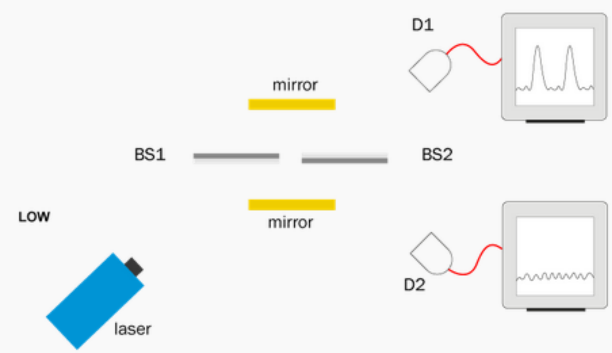

Figure 1: Experiment 5.

We set up the experiment with the lengths of the two paths between the beam splitters such that the wave following the upper path that is reflected from beam splitter BS2 has a phase that is exactly the same phase as the transmitted wave entering BS2 on the lower path. But the phase of the wave on the lower path reflected from BS2 is exactly opposite to that of the transmitted wave entering BS2 on the upper path. (How the beam splitters are arranged to achieve this is explained in How do we describe the action of a beam splitter). The device in Figure 1 is called a Mach-Zehnder interferometer.

When we set the laser to high intensity ("high"), there is now no signal in detector D2, and all the light is detected by detector D1. This is a well-known classical effect of interference.

We now reduce the power of the laser again all the way down to the single photon level (setting "low"). The current in detector D1 decreases until only single current pulses appear. Detector D2 stays silent. This is consistent with Experiment 4 (Can a photon be divided into parts?), where the classical signal also reduces to pulses in the current. What is the problem?

In What is a photon and Can a photon be divided into parts? we see that photons are particles that are randomly either reflected or transmitted at the beam splitter. How can a single particle cause interference such that detector D2 remains dark?

We have established that photons are indivisible, so the explanation cannot be that the photon splits into two smaller parts at the first beam splitter and recombines at the second beam splitter to always trigger detector D1. If the photon does not split itself between the two paths, a natural question to ask is: which of the two paths between the two beam splitters does the photon take, the top or the bottom? To answer this, we need to modify our experiment (see Which path does a photon take?).

Simulation	Step-by-step Exploration	quantumphysics.iop.org	University of St Andrews	IOP Institute of Physics

Interferometer experiments with photons, particles and waves

Type a term or article name here

- What is the Copenhagen interpretation?
- What are hidden variables
- How do we describe the quantum state of two particles?
- Why do we need complex numbers in quantum physics?
- Can a photon be divided into parts?
- How is the electron spin state represented in quantum mechanics?
- How do we describe the general state of a photon?
- How do we find out the energy state of an atom?
- What is a qubit?
- How do we calculate probabilities
- How do we calculate energies in the Bohr model?
- What can and what can't we learn from experiment?
- Can different observables each give a definite outcome when measured together?
- What is a wave-function
- What is wave-particle duality?
- How is quantum spookiness confirmed? - Bell's theorem
- How does a gravitational interferometer work?

GLOSSARY

- absorption lines
- beam splitter
- gravitational waves
- Mach–Zehnder interferometer

A device which initially splits a beam of light and, having reflected the split beams through separate test pathways, recombines them to examine any phase difference between the beams and the resulting interference pattern that may have been established. Typically employs a light source (often a laser), a pair of beam splitters, a pair of mirrors and an appropriate set of detectors.

- photoelectric effect
- two-level atom
- two level atom

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There is an extensive hyperlinked glossary of terms

GLOSSARY

absorption lines

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ARTICLE

How can particles interfere

GLOSSARY

Mach-Zehnder interferometer

phase

SIMULATIONS

Interferometer experiments with photons, particles and waves

SIMULATION PROBLEMS

Interferometer experiments with photons, particles and waves - Problems

Simulation | **Step-by-step Exploration**

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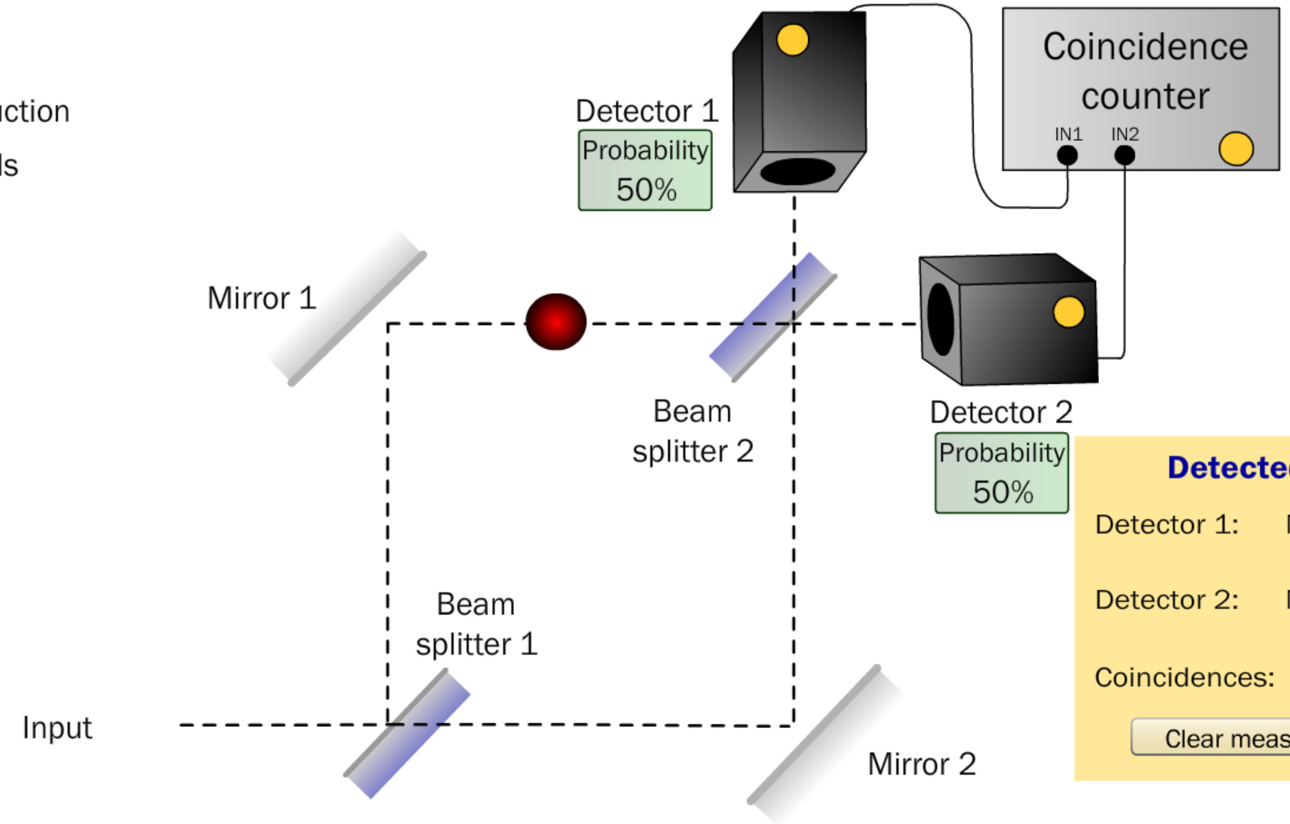
Interferometer experiments with photons, particles and waves

- Introduction
- Controls



Detected counts

Detector 1: $N_1 = 24$

Detector 2: $N_2 = 26$

Coincidences: $N_c = 0$

Clear measurements

Input

- Classical particles
- Electromagnetic wave
- Single photons

Main Controls

- Fire Particle
- Continuous Fire
- Fast forward 50 counts
- Remove second beam splitter

Display controls

- [x] Label elements
- [x] Show theoretical probabilities

ARTICLE

How can particles interfere

GLOSSARY

Mach-Zehnder interferometer

phase

SIMULATIONS

Interferometer experiments with photons, particles and waves

SIMULATION PROBLEMS

Interferometer experiments with photons, particles and waves - Problems

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quantumphysics.iop.org/#!sproblem/interference/interferometer-experiments-with-photons-particles-and-waves-problems

QUANTUM PHYSICS

For these problems, use the simulation "Interferometer experiments with photons, particles and waves".

1. Have a play with the simulation for a few minutes, getting to understand the controls and displays. Note down five things that you have found out.
2. Consider the case with just a single beamsplitter present in the experiment.
    1. Compare the experimental results for classical particles with those for electromagnetic waves. List ways in which the results are similar and different. Explain the differences you find in terms of how each behaves when passing through the experimental apparatus.
    2. Compare the experimental results for single photons with those for classical particles and for electromagnetic waves. With just a single beam splitter present, how are single photons similar to classical particles, and how are they similar to electromagnetic waves?
3. Now consider the case with two beam splitters inserted into the experimental setup, but with zero phase shift in the lower path.
    1. Compare the experimental results for classical particles and for electromagnetic waves. List ways in which the results are similar and different. Explain the differences between the two in terms of how each behaves after encountering the second beamsplitter.
    2. Compare the experimental results for single photons with those for classical particles and for electromagnetic waves. With two beam splitters present (and no phase shift), how are single photons similar to classical particles, and how are they similar to electromagnetic waves?
4. Now consider the case with two beam splitters present in the experimental setup, and a non-zero phase shift in the lower path.
    1. As the magnitude of the phase shift in the lower path is varied, how do the experimental results for single photons and electromagnetic waves compare?
    2. Is the behaviour of a single photon at the first beamsplitter changed by the presence of a second beamsplitter? Does its behaviour at the first beamsplitter depend on whether or not there is a non-zero phase shift in the lower path?

Type a term or article name here

ARTICLE

- How can particles interfere

GLOSSARY

- Mach-Zehnder interferometer
- phase

SIMULATIONS

- Interferometer experiments with photons, particles and waves

SIMULATION PROBLEMS

- Interferometer experiments with photons, particles and waves - Problems
- Which path does a photon take?
- How do classical concepts break down?
- How do we describe the general state of a photon?
- How do we describe the superposition of states
- Why do we need complex numbers in quantum physics?
- What is state space
- What is the point of Dirac notation?
- How do we calculate probabilities
- What is an expectation value?
- How does a gravitational interferometer work?

For these problems, use the simulation "Interferometer experiments with photons, particles and waves".

1. Have a play with the simulation for a few minutes, getting to understand the controls and displays. Note down five things that you have found out.

2. Consider the case with just a single beamsplitter present in the experiment.
    1. Compare the experimental results for classical particles with those for electromagnetic waves. List ways in which the results are similar and different. Explain the differences you find in terms of how each behaves when passing through the experimental apparatus.

    2. Compare the experimental results for single photons with those for classical particles and for electromagnetic waves. With just a single beam splitter present, how are single photons similar to classical particles, and how are they similar to electromagnetic waves?

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QUANTUM PHYSICS

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SIMULATIONS

Interferometer experiments with photons, particles and waves

SIMULATION PROBLEMS

Interferometer experiments with photons, particles and waves - Problems

Which path does a photon take?

How do classical concepts break down?

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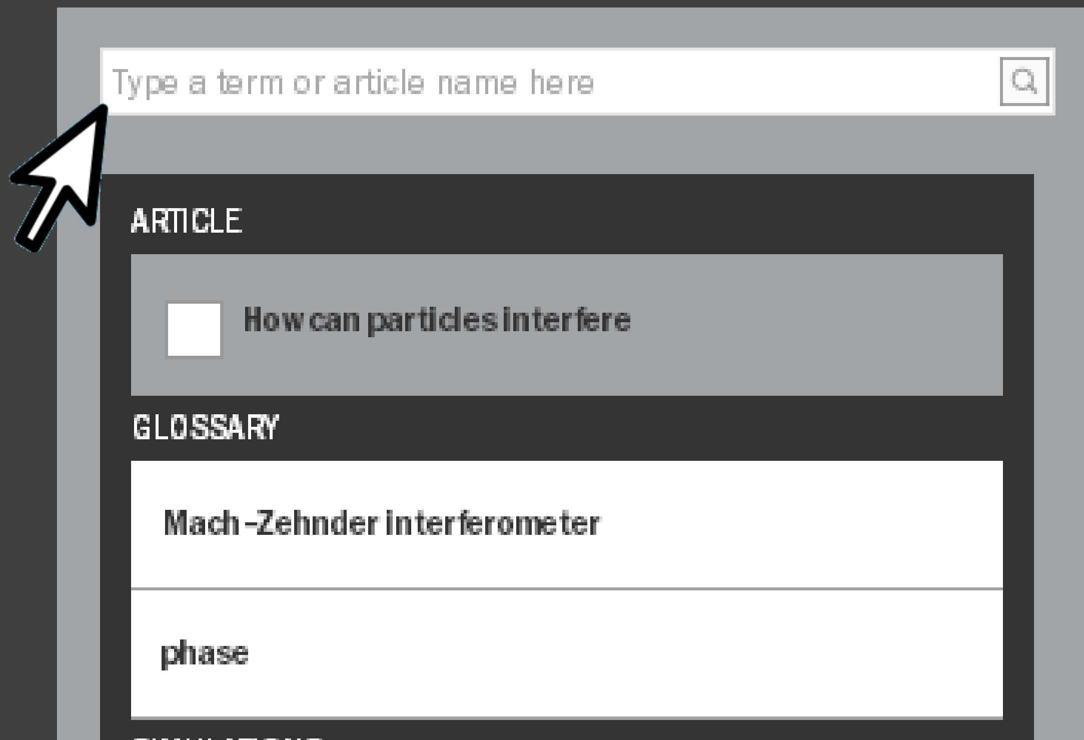
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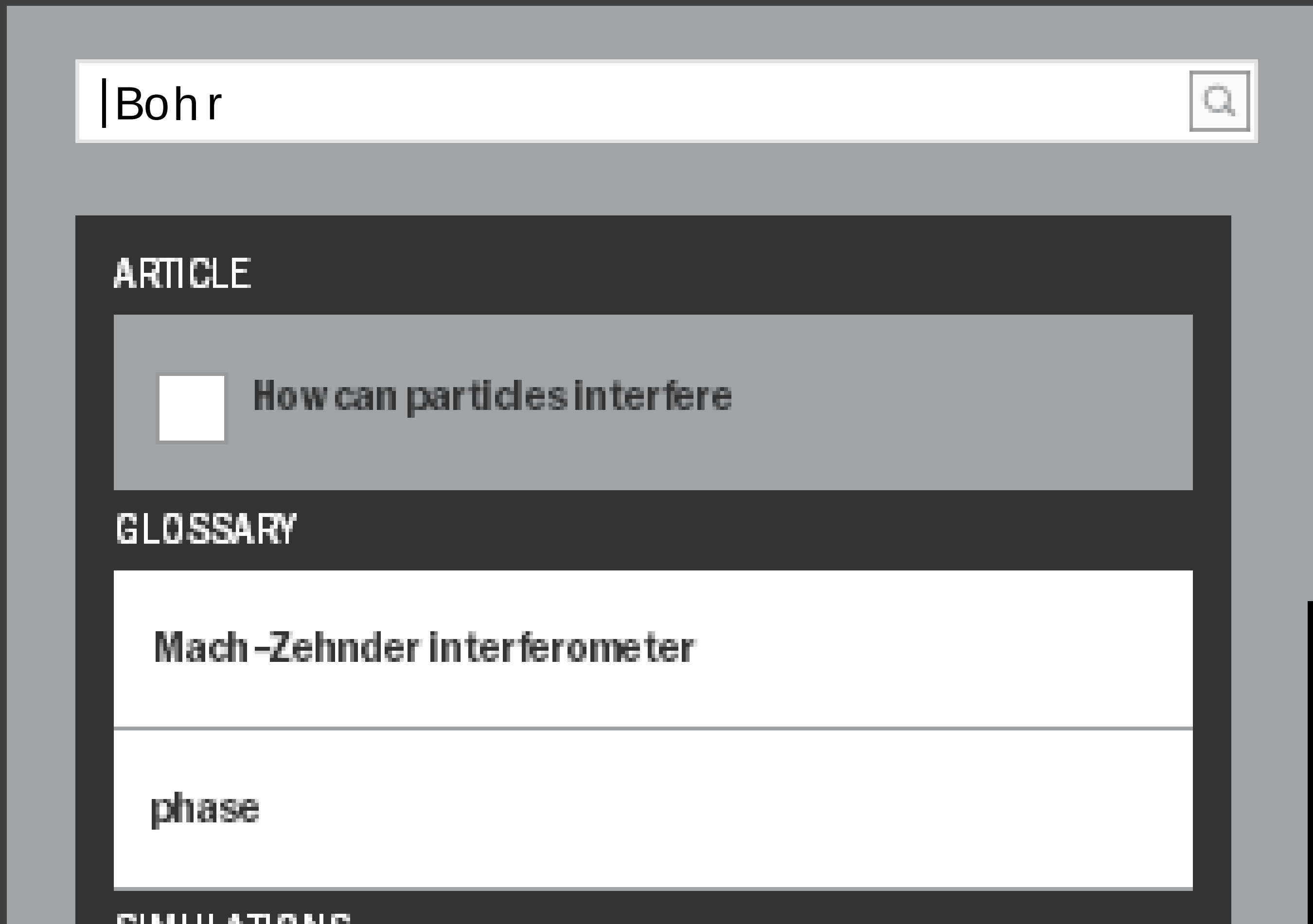
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GLOSSARY
Mach-Zehnder interferometer
phase
SIMULATIONS

Bohr

ARTICLES

- What is the Bohr model of atomic structure
- What is the Copenghagen interpretation?
- How do we find out the energy state of an atom?
- How do we calculate energies in the Bohr model?
- How is quantum spookiness confirmed? - Bell's theorem

GLOSSARY

Bohr model

Bohr radius

Copenhagen interpretation

Using articles or simulations in lectures

Can I get a list of all material on the site?

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Solutions to problems

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