Concepts of Physics: Homework 10 Solution

Due: 18 November 2022

1 Wavelength and diffraction of neutral atoms

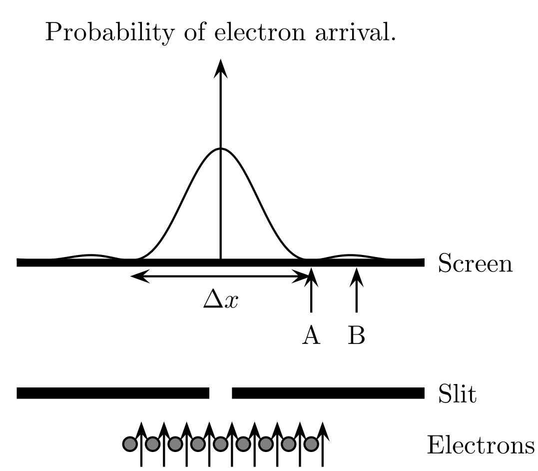
In separate experiments neon atoms and argon atoms are fired with the same speed toward the same single slit and screen arrangement. Explain your answers for the following.

a) Which of the following is true?
   i) The wavelengths of the neon atoms and the argon atoms are 0 m.
   ii) The wavelengths of the neon atoms and the argon atoms are the same but is non-zero.
   iii) The wavelength of the neon atoms is larger than that of the argon atoms.
   iv) The wavelength of the neon atoms is smaller than that of the argon atoms.

b) Which of the following is true about the central region in which most of the atoms arrive on the screen?
   i) The central region is the same for both.
   ii) The central region is wider for neon.
   iii) The central region is wider for argon.

2 Particles passing through a single slit

A beam of electrons is fired toward a barrier which is impenetrable everywhere except through slit, which is so narrow that an electron can only just pass through. The initial direction of each electron's motion is vertical (absolutely no horizontal component). The probability distribution (curve) for the electron's arrival at various points along the screen is illustrated.



a) Suppose that an electron arrives at the screen. In this case what would be a reasonable answer to the question: "Did the electron passed through the slit or not?"

b) Is it possible for an electron to hit the screen at point A?

c) Is it possible for an electron to hit the screen at point B?

d) Only those electrons that were aimed precisely at the slit will ever pass through and their states of motion prior to arrival at the slit will be identical. What does this probability distribution imply regarding the point at which any one of these electrons strikes the screen? Will it always strike the screen at the same point? Explain your answers.

e) In this scenario, all that the electrons all started with the same initial state of motion. Compare this to dropping a set of balls, one at a time, from the same point through a sufficiently wide slit. Would they all land at the same spot? Would your intuition (or equivalently classical physics) predict that the electrons will arrive at the same point on the screen? How does this compare to your answer to part (d)? Explain your answers.

f) Is the physical world deterministic (i.e. the future state of a physical system only depends on its current state and the interactions it experiences) or is it contain elements of randomness? Justify your answer based on answers to previous parts of this question.

3 Particles passing through a double slit

Consider a beam of electrons fired at a double slit barrier as illustrated in Fig. 1. Each electron which passes through the left slit is painted red by an ink jet without affecting its motion. Those passing through the right are painted blue. Fig. 1 shows the probability distributions for finding red and blue electrons at locations on the screen.

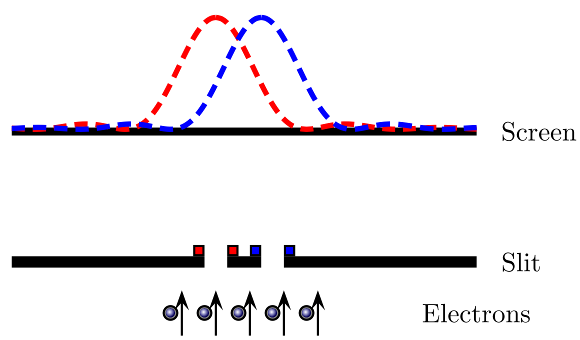


Figure 1: Two slits with color markers.

a) The electron color describes through which slit it passed. Determine the probability with which an electron arrives at various points on the screen, **regardless of the color.** Sketch the probability distribution for this.

b) Now suppose that the ink jets are turned off. Again, one aims to determine the probability distribution for an electron hitting the screen. A remarkable feature of quantum physics that the intuitive answer to this is completely incorrect. The probability distribution is illustrated by the solid line in Fig. 2. The dashed lines indicated the probabilities with the color markers.

   Compare the distribution of Fig. 2 to that which you obtained in part (a). Are there any locations where no electrons will ever arrive? Did the distribution in your answer to part (a) make the same prediction for those locations?

One feature of these experiments is that a single electron can only pass through one slit. This can be verified by turning both ink jets on and checking whether an electron ever emerges with both colors. Experiments show that it only emerges with one. Based on this, one would be tempted to say that the electron either passes through the left or the right slit but not both.

c) Suppose that an electron is fired toward the double slit barrier with the ink jets turned **off.** If it does pass through the left hand slit identify any locations where it could arrive according to Fig. 1 but at which it cannot arrive according to Fig. 2. Repeat this procedure assuming that the electron passes through the right slit. Identify at least

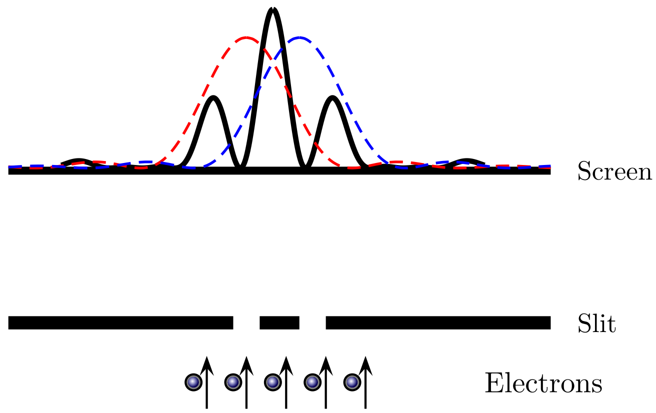


Figure 2: Actual two slit probability distribution (solid black) with the two single slit distribution patterns (dashed colored).

one location at which the electron could arrive according to Fig. 1 for both the left and right slit cases but at which it cannot arrive according to Fig. 2. Noting that Fig. 2 is actually consistent with experimental observations, can one say that the electron could possibly only have passed through one slit?

4 Wavelength of a baseball

A baseball has mass $0.14\,\mathrm{kg}$.

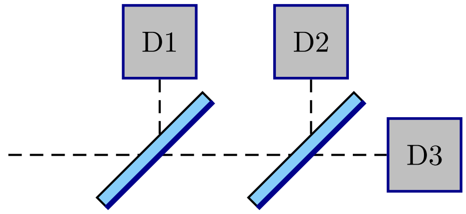
a) Determine the wavelength of a baseball that moves with speed $100\,\mathrm{m/s}$.

b) Observing any wave effects requires passing the waves through openings which are separated by distances comparable with the wavelength of the wave. Use this and the fact that the width of a nucleus of an atom is approximately $10^{-15}\,\mathrm{m}$ to explain why one never observes wave effects from baseballs despite the fact that one can observe wave effects in interference experiments for light (typical wavelengths $5.0 \times 10^{-7}\,\mathrm{m}$).

5 Interference experiments with photons

Many interference experiments use optical devices called beamsplitters. Consider beamsplitters, each of which reflects a photon with probability 1/2 and lets it pass with probability 1/2.

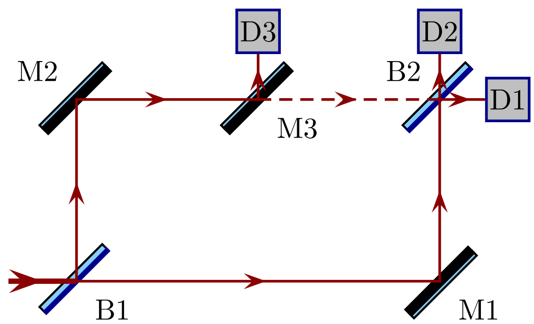
a) Consider the illustrated arrangement of beamsplitters and detectors.



Suppose that 800 photons are fired toward the first beamsplitter. Determine roughly how many will be detected in each of the detectors.

b) Determine the probabilities with which a photon from the left toward the first beamsplitter will be detected by detector D1, detector D2 and detector D3.

c) Consider the illustrated apparatus. Beamsplitters are labeled B and mirrors M. If the mirror labeled M3 is removed, it is found that every photon arrives at detector D2 and none at detector D1.



Now suppose that mirror M3 is present. If a photon strikes mirror M3 it will be detected by detector D3 with certainty. For the rest of the exercise, suppose that mirror M3 is present, a photon is fired into the apparatus and is *not* detected by detector D3. Would you say that the photon definitely did not pass along the upper path (i.e via mirror M2)? Would you say that the photon interacted at all with M3?

d) Given that the photon is not detected by detector D3, what are the probabilities with which it will be detected by detector D1 and detector D2? Would you say that, in this case, the fact that mirror M3 is *present* affected what happened to the photon compared to if it were *absent?*

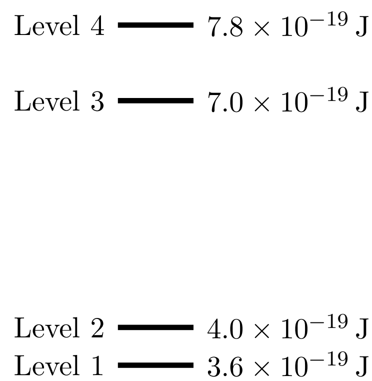
e) In this case does it appear that M3 actually interacted with the photon? Does this suggest that one object (M3) can have an effect on another (the photon) with any interaction between them? How does this compare to your everyday experiences of the world?

6 Hobson, *Physics, Concepts and Connections, 5ed*, Ch 13, Problem 4, page 321.

7 Hobson, *Physics, Concepts and Connections, 5ed*, Ch 13, Problem 6, page 321.

8 Atom emission

An artificial atom has four energy levels as illustrated. The atom can make transitions between any of these energy states.



a) Determine the largest energy that any photon emitted by the atom could have.

b) Determine the smallest energy that any photon emitted by the atom could have.

c) Determine the largest frequency that any photon emitted by the atom could have.

d) Determine the frequency of the photon emitted by the atom when it drops from level 3 to level 2.