

Episode 507: Electron standing waves

You could extend the idea of electrons-as-waves further, to the realm of the atom.

Summary

Demonstration: Melde's experiment. (20 minutes)

Discussion: Electron waves in atoms. (10 minutes)

Demonstration: Standing waves on a loop. (10 minutes)

Student Question Electron standing waves (10 mins)

Demonstration:

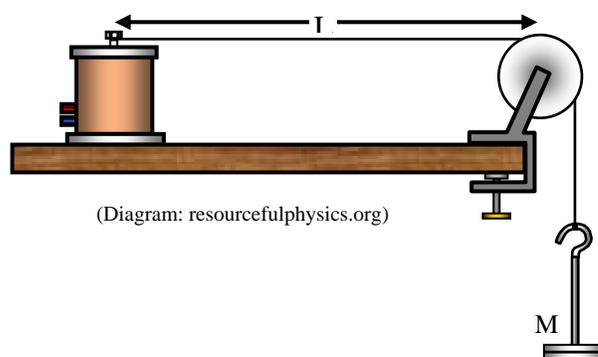
Melde's experiment

TAP 507-1: Standing waves – for electrons?

In this section we are going to introduce the idea of standing waves within an atom. It is therefore useful first to demonstrate standing waves on a stretched elastic cord. This is known as Melde's experiment.

(A very simple alternative to the vibration generator is an electric toothbrush.)

Show that there are only certain frequencies at which standing wave loops occur.



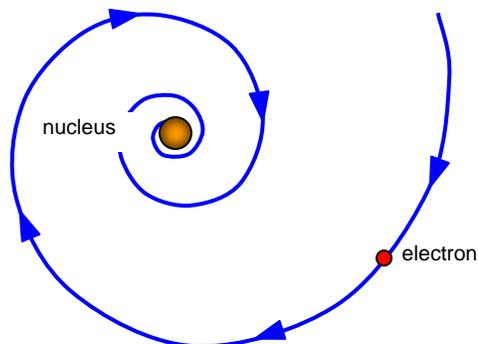
Discussion:

Electron waves in atoms

The waves on the string are 'trapped' between the two fixed points at the ends of the string and cannot escape.

If the electron has wave properties and it is also confined within an atom we could imagine a sort of standing wave pattern for these waves rather like the standing waves on a stretched string. The electrons are 'trapped' within the atom rather like the waves being 'trapped' on a stretched string. The boundaries of these electron waves would be the potential well formed 'within' the atom.

This idea was introduced because the simple Rutherford model of the atom had one serious disadvantage concerning the stability of the orbits. Bohr showed that in such a model the electrons would spiral into the nucleus in about 10^{-10} s, due to electrostatic attraction. He therefore proposed that the electrons could only exist in certain states, equivalent to the loops on the vibrating string.



If your students have met the idea of angular momentum, you could tell them that Bohr proposed that the angular momentum of the electrons in an atom is quantised, in line with Planck's quantum theory of radiation. He stated that the allowed values of the angular momentum of an electron would be integral multiples of $h/2\pi$. This implied a series of discrete orbits for the electron. We can imagine the electron as existing as a wave that fits round a given orbit an integral number of times.

Demonstration:

Standing waves on a loop

The wire loop is a two dimensional analogy of electron waves in an atom. As it vibrates at the correct frequency, an integral number of waves fit round the orbit. These waves represent the electron waves in an atom.

Student question:

Electron standing waves

de Broglie waves can be imagined as forming standing waves which fit into an atom

TAP 507-2: Electron standing waves

TAP 507-1: Standing waves - for electrons?

Electrons have a frequency too

Electrons can be modelled as having a frequency. In another context you have seen how superposition of waves in the laboratory produces standing waves. Here it is useful to put these two together, describing electrons with standing waves, with their wavelength described by de Broglie's relationship:

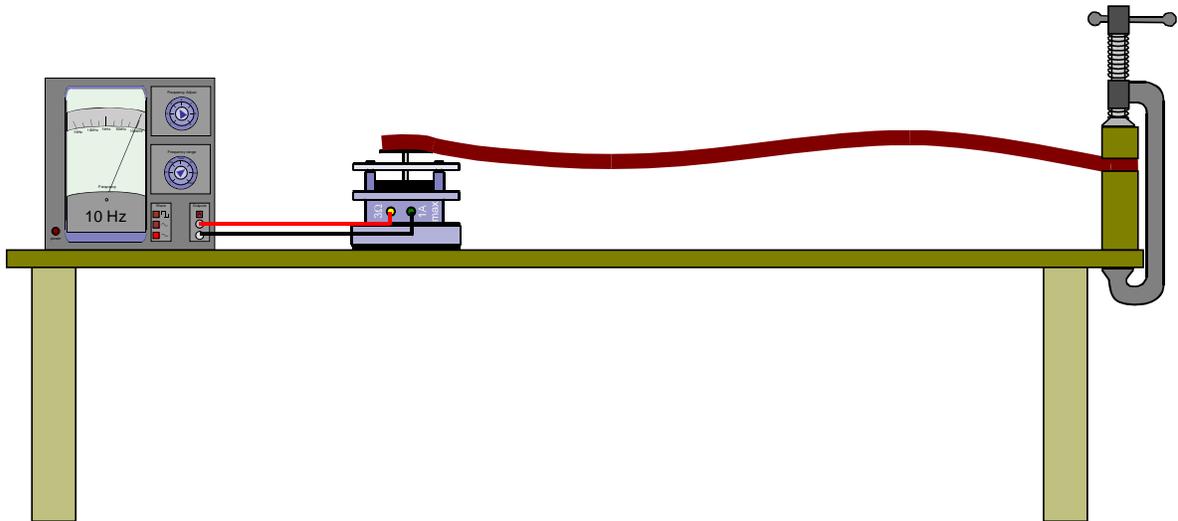
$$\lambda = h / mv.$$

Here you look at some consequences of this step.

You will need:

- ✓ vibration generator
- ✓ signal generator
- ✓ rubber cord
- ✓ G-clamp
- ✓ wooden blocks

Vibrating a rubber cord

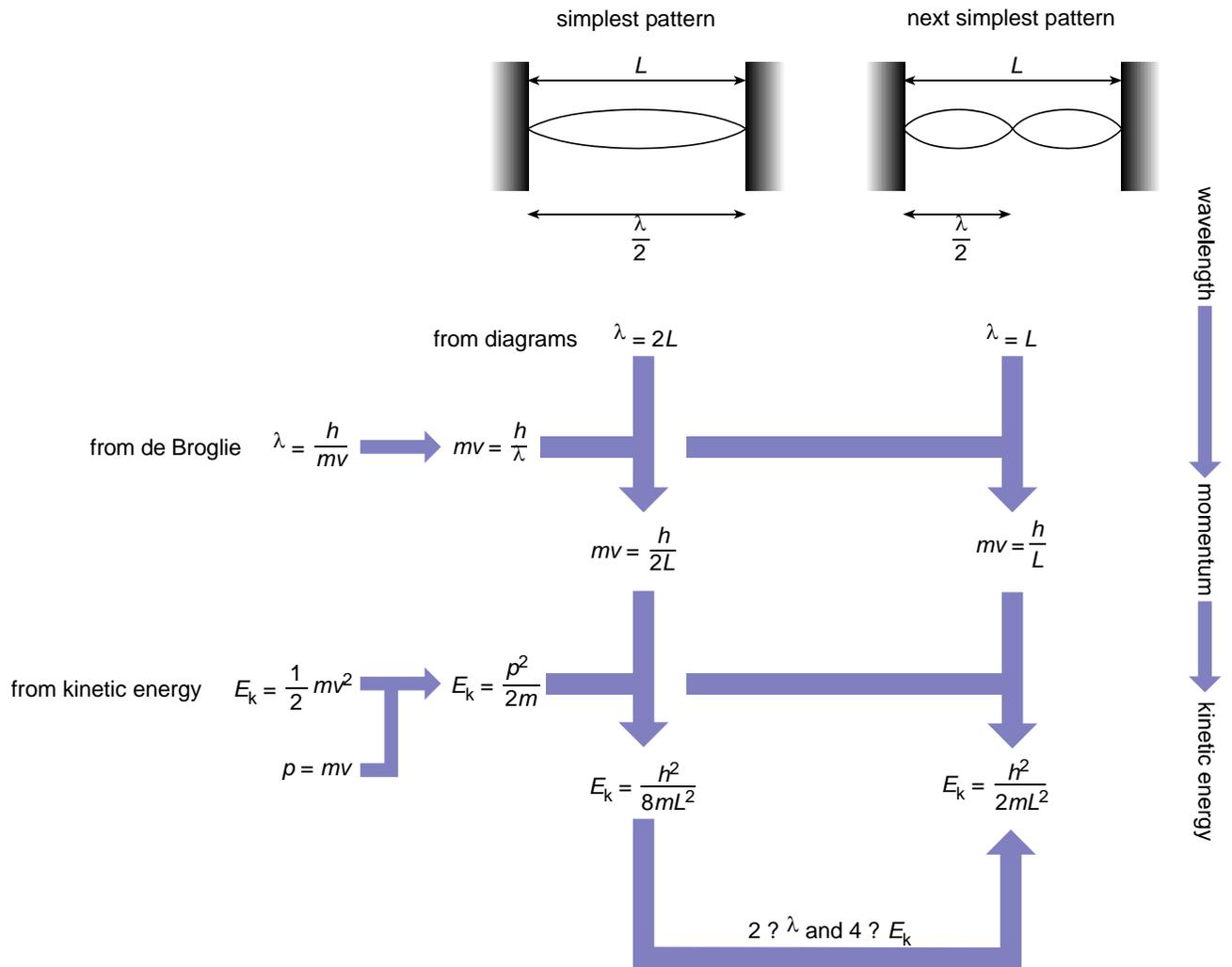


Make sure that you can get clear patterns with this apparatus. Note that only whole numbers of half wavelengths fit onto the cord.

Electrons trapped in an atom are also constrained. Describing them as waves, where the amplitude tells you the chance of find them in any one place, constrains you to draw the waves in a similar way.

Making links

Putting relationships together with these results allows you to predict that electrons will have certain allowed energy levels only.



See if you can continue the series for the next two standing wave patterns that will fit onto the cord.

You have

1. Reminded yourself about standing waves.
2. Seen some of the consequences of using standing waves to model electrons in atoms.

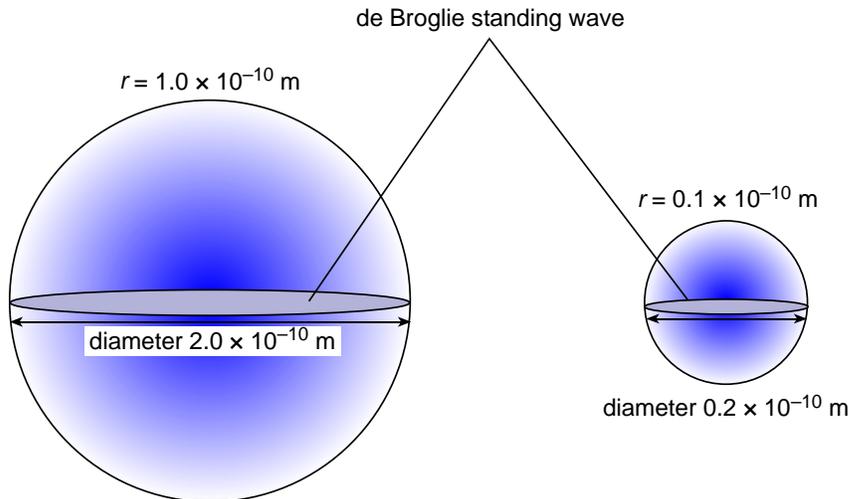
External reference

This activity is taken from Advancing Physics chapter 17, 140E

TAP 507-2: Electron standing waves

If an electron is confined in a definite space, the de Broglie waves can be imagined as forming standing waves that fit into that space.

$h = 6.6 \times 10^{-34}$ J s, charge on electron = 1.6×10^{-19} C, mass of electron is 9.1×10^{-31} kg



Suppose the standing wave fits with one half-wavelength across the diameter of the atom.

1. Write down the wavelength of the standing wave if the atom is imagined to have radius $r = 1.0 \times 10^{-10}$ m.
2. Write down the wavelength of the standing wave if the atom is imagined ten times smaller, with radius $r = 0.1 \times 10^{-10}$ m.
3. Other standing waves could fit inside the same diameter. Would their wavelengths be longer or shorter than the waves shown here?

Electron momentum

The momentum of an electron with de Broglie waves of wavelength λ is $m v = h / \lambda$. If the wavelength is the largest possible, the momentum must be the smallest possible.

4. Calculate the smallest possible momentum of the electron, if the atom is imagined to have radius $r = 1.0 \times 10^{-10}$ m.

5. Calculate, or write down directly from the answer to question 4, the smallest possible momentum of the electron if the atom is imagined to have radius $r = 0.1 \times 10^{-10}$ m.

6. Write a few lines explaining why an electron confined in a smaller space has a larger minimum momentum.

Answers and worked solutions

1. The waves have half a wavelength fitting into the diameter, so $\lambda = 4.0 \times 10^{-10}$ m.
2. The radius is 10 times smaller so the wavelength is 10 times shorter: $\lambda = 0.4 \times 10^{-10}$ m.
3. More half-wavelength loops have to be fitted into the same length, so the wavelengths will all be smaller.
- 4.

$$\begin{aligned}mv &= \frac{h}{\lambda} \\ &= \frac{6.6 \times 10^{-34} \text{ J s}}{4.0 \times 10^{-10} \text{ m}} \\ &= 1.65 \times 10^{-24} \text{ kg m s}^{-1}.\end{aligned}$$

5. As for question 4 with the wavelength 10 times smaller, so the momentum is 10 times larger: $mv = 16.5 \times 10^{-24} \text{ kg m s}^{-1}$.
6. The smaller the space the shorter the wavelength. But the shorter the wavelength the greater the momentum, since $mv = h / \lambda$.

External reference

This activity is taken from Advancing Physics chapter 17, and uses part of question 160s.