SEEING WITH ^{2}He 4.0026 ATOMS

Beam Energy

How do we make sure the helium atom beam will produce an image with enough detail for us to do cutting-edge research on our samples?

Overview:
Beam Energy

Stage 1:
Beam Source

Stage 2:
Creating the Beam

Stage 3:
Contrast

Stage 4:
Creating an Image

GCSE Physics	Momentum	$p = mv$	Kinetic Energy	$\frac{1}{2}mv^2 = \frac{p^2}{2m}$	EM Spectrum	$v = f\lambda$
A Level Physics	Wave particle duality	$p = \frac{h}{\lambda}$	Diffraction	$d\sin\theta = n\lambda$		

Introduction & context

Scanning helium microscopes (SHeM) could open a new window on to the surface structure of materials. This technique is cutting-edge and is still being developed. Currently only three helium microscopes exist in the world. The aim of such microscopes is to be able to take pictures of the surface of materials without causing damage, as in the case of electron microscopy, and in situations where optical microscopes are not appropriate, for example when imaging transparent materials.

What determines the detail that we can image?

The level of detail in an image is typically called the *resolution*. The wavelength of our beam determines the theoretical best resolution of the image that we record because the beam of atoms is diffracted as it passes through the small hole that creates the beam. For example, if two dots are less than a distance d apart the instrument will image them as one oval blob rather than *resolve* them as two separate features.

The distance d depends on the wavelength of the beam (λ) and the size of the hole that the atoms pass through. For modern microscopes, this means that $d \approx \lambda/2$ (known as the Abbe limit).

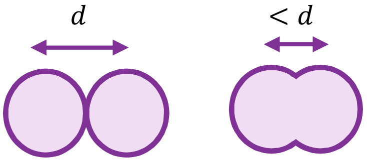

Diagram illustrating how detail can be lost in image due to the resolution of the imaging instrument. ***Left:*** *The two circles separated by a distance equal to the resolution of the microscope and so appear in the image as two separate circles.* ***Right:*** *The two circles are closer together than the resolution limit of the microscope and therefore they appear blurred into one shape in the image.*

Microscopes that use light (optical) can separate features that are more than $250\,\mathrm{nm}$ apart because the typical wavelength of visible light is $500\,\mathrm{nm}$. To resolve details smaller than this you need either shorter wavelength light (for example X-rays) or to use a matter beam.

A beam of atoms has a wavelength?

The nature of light has been long debated and we can think of it as both waves and particles. Similarly, we can think of matter as behaving as particles or as waves.

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Related Concepts

Waves
Diffraction

Related Questions

GCSE Book Section 38A - Q17	⬢
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Single Slit Diffraction	⬢⬢
X-ray Crystallography	⬢⬢

The de Broglie relation enables us to calculate the equivalent wavelength of our helium atoms

$$\lambda = \frac{h}{p}$$

where h is the Planck constant ($6.626 \times 10^{-34}\ \mathrm{J\ s}$) and $p = mv$ is the momentum of the particle. The momentum of an atom and its kinetic energy is related by

$$E = \frac{p^2}{2m}$$

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Related Concepts

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GCSE Book Section 34 – Q3

Light Pressure

Putting these two equations together we see that the wavelength of an atom beam depends on the mass of the atom and the energy it has in motion.

$$p = \sqrt{2mE}, \quad \lambda = \frac{h}{\sqrt{2mE}}$$

As we increase the energy of the atoms in the beam, their wavelength decreases, and as we increase the mass of the atom in the beam, the wavelength also decreases.

Producing high resolution images

Our ultimate resolution (ability to separate details $\geq d$) depends on the wavelength. A longer wavelength reduces the resolution of our image, meaning we can see less detail. So we want to shorten the wavelength as much as possible. We can do this by

1. Increasing the energy of the atom beam or,
2. Increasing the mass of the atoms in the beam.

As an example, let us say that we want to be able to separate details that are at least $50\ \mathrm{pm}$ apart (the diameter of an atom is about $100\ \mathrm{pm}$, a typical human hair is $50{,}000{,}000\ \mathrm{pm}$ thick).

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Related Questions

Electron Beam

$$E = \frac{h^2}{2m\lambda^2} = \frac{(6.626 \times 10^{-34})^2}{2 \times 9.11 \times 10^{-31} \times (50 \times 10^{-12})^2} \approx 600\ \mathrm{eV}$$

If we have a low mass particle, like an electron ($m_e \approx 9.11 \times 10^{-31}\ \mathrm{kg}$), then we need them to have high energy, which means that they will damage the sample that we are trying to image.

If we have a relatively high mass particle, like a helium atom ($m_{\mathrm{He}} \approx 6.72 \times 10^{-27}\ \mathrm{kg}$), then to produce the same wavelength the energy of each atom can be much smaller (nearly $10{,}000$ times smaller).

$$E = \frac{h^2}{2m\lambda^2} = \frac{(6.626 \times 10^{-34})^2}{2 \times 6.72 \times 10^{-27} \times (50 \times 10^{-12})^2} \approx 0.08\ \mathrm{eV}$$

What is the result?

Using helium atom beams instead of electrons means that we can theoretically resolve small features without needing a high energy beam. Samples can therefore remain intact after imaging, allowing repeated experiments on the sample to be performed using an atom beam.

In a real helium microscope, other practical constraints (such as taking an image in a finite amount of time) mean that the actual resolution is lower than the theoretical diffraction limit that can be calculated from the wavelength.