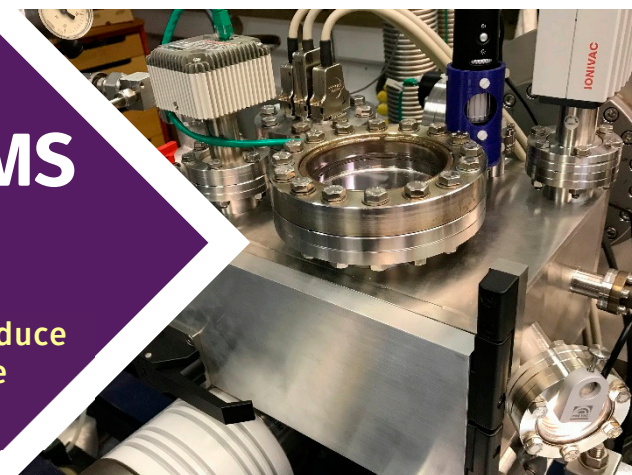


SEEING WITH ²He ATOMS

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?



<div><div>Overview: Beam Energy</div><div>Stage 1: Beam Source</div><div>Stage 2: Creating the Beam</div><div>Stage 3: Contrast</div><div>Stage 4: Creating an Image</div></div>						
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).

Microscopes that use light (optical) can separate features that are more than 250 nm apart because the typical wavelength of visible light is 500 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.

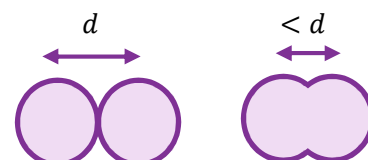


Diagram illustrating how detail can be lost in image due to the resolution of the imaging instrument. **Left:** The two circles separated by a distance equal to the resolution of the microscope and so appear in the image as two separate circles. **Right:** The two circles are closer together than the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



Related Concepts

Waves
Diffraction



Related Questions

GCSE Book Section 38A - Q17
Finding Frequency
Essential Pre-University Physics D4.1
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 (6.626×10^{-34} J s) and $p = mv$ is the momentum of the particle. The momentum of an atom and its kinetic energy is related by

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

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 pm apart (the diameter of an atom is about 100 pm, a typical human hair is 50,000,000 pm thick).

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

If we have a low mass particle, like an electron ($m_e \approx 9.11 \times 10^{-31}$ 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 ($m_{\text{He}} \approx 6.72 \times 10^{-27}$ kg), then to produce the same wavelength the energy of each atom can be much smaller (nearly 10,000 times smaller).

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

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.



Related Concepts

Waves



Related Questions

GCSE Book Section 34 – Q3
Light Pressure



Related Questions

Electron Beam

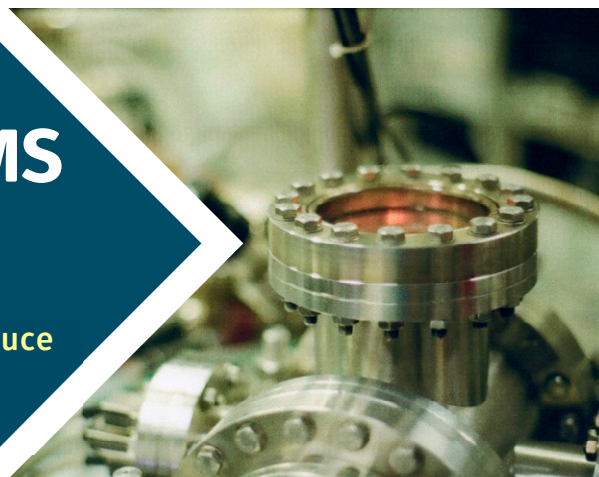


SEEING WITH ²He ATOMS

Beam Source



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

Kinetic Energy

$$\frac{1}{2}mv^2$$

Pressure

$$P = \frac{F}{A}$$

Density of
Materials

$$\rho = \frac{m}{V}$$

A Level Physics

Ideal Gas Law

$$PV = Nk_B T$$

Internal
Energy

$$\frac{3k_B T}{2}$$

Kinetic Theory of
Gases

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$$

Introduction & context

In a scanning helium microscope (SHeM), a beam of helium atoms is directed onto a sample. The beam is formed by a nozzle in the vacuum chamber. This nozzle releases helium into the chamber at high pressure so the pressure difference between the source and the vacuum chamber causes the gas to accelerate out into the chamber, expanding into the volume. The pressure in the vacuum chamber (0.0000001 atm) is low enough that there are no gas particle collisions and the atoms travel in straight lines.

In the expansion, the lack of collisions means that they travel in straight lines in the forward direction.

Gas particle collisions

In a gas, particles are far apart and free moving but will still collide with each other. For example, in air particles typically move by about 100 nm before colliding with another particle. These gas particle collisions cause it to act like a fluid and introduce effects such as turbulence.

Therefore, if a beam of atoms were created at atmospheric pressure it would quickly dissipate due to collisions with other particles.

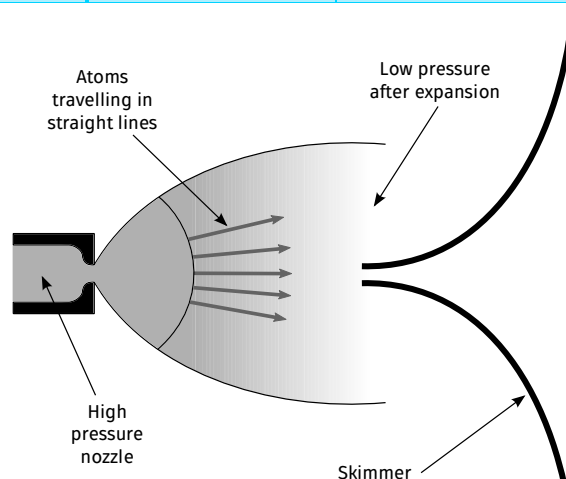
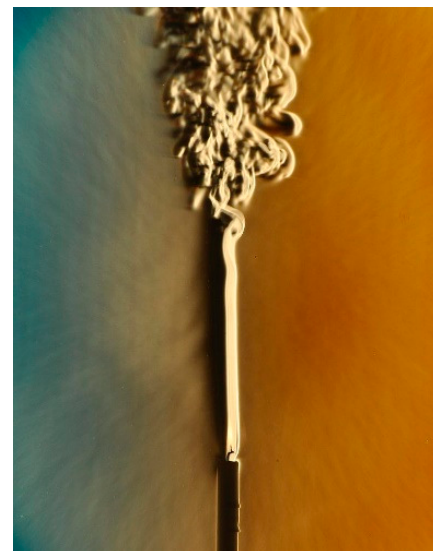


Diagram showing the expansion of helium gas from a high pressure nozzle into a vacuum chamber. A skimmer is used to select the centre line of helium atoms to create the atom beam source.



Thermal convection plume rising from an ordinary candle in still air. Image from Wikipedia user Gary Settles.



Related Questions

GCSE Book Section 60 – Q8

An Indecisive Gas

Brownian Motion



Beam formation

To reduce the background particles that will attenuate the atom beam, the entire experiment (source, sample and detector) is performed in a vacuum chamber. The beam of atoms is created in a chamber that has a pressure about $1/100,000$ of atmospheric pressure. For comparison, the pressure in a vacuum cleaner is only about $1/5$ of atmospheric pressure. In fact, other parts of the experiment are held at even lower pressures, with pressures as low as $1/10^{14}$ of atmospheric pressure.

Once the atoms are travelling in straight lines, the centre part of the expansion is selected with a skimmer so that the beam only contains atoms moving in a forward direction. Therefore, a beam of atoms can then be created without any scattering while it travels to the sample.

Particle theory of gases

The particle theory of matter is a model that says that all matter is made up of particles, which behave differently depending on what state the matter is in. **Solids** are made up of particles that are tightly bound together. **Liquids** contain particles that are still bound closely together, but can now move past each other allowing the liquid to flow. A **gas** contains particles that are far apart and essentially free moving.

The source of helium atoms in our experiment is a gas, contained in a high pressure cylinder. The gaseous helium atoms enter the vacuum chamber through a nozzle. The nozzle is at room temperature. According to the kinetic theory of gases we can calculate how the speed of the helium atoms depends on this nozzle temperature.

We can relate the average velocity of a gas particle ($\overline{v^2}$) to the temperature of the gas using the **kinetic theory of gases**. In this model, N gas particles, each of mass m , collide with the walls of a cubic container volume V , exerting a pressure P , given by

$$P = \frac{F}{A} = \frac{Nm\overline{v^2}}{3V}$$

The ideal gas law relates PV to the temperature of the gas such that

$$PV = Nk_B T$$

Combining these two results, we can relate the average kinetic energy per particle to the temperature of the gas.

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$$

Since the gas particles can move in three perpendicular directions (x, y, z), we see that in this model each direction contributes $\frac{1}{2}k_B T$ to the average kinetic energy of the atoms. This is a simplified model and the way that the gas expands through the nozzle contributes an additional $k_B T$ to the energy of the atoms. The average velocity of the helium gas atoms in the SHeM is given by

$$\frac{1}{2}m\overline{v^2} = \frac{5}{2}k_B T, \quad v_{rms} = \sqrt{\frac{5k_B T}{m}}$$

The temperature of the nozzle is 293 K, $k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$, and $m = 4.00 \times 1.66 \times 10^{-27} \text{ kg}$. This means that the average speed of the helium atoms is $v_{rms} \approx 1740 \text{ m s}^{-1}$.



Related Questions

[Atmospheric Pressure](#)



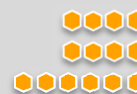
Related Concepts

[GCSE Book Section 17](#)
[Ideal Gases](#)



Related Questions

[Essential Pre-University Physics G2.7](#)
[Gaseous Ideals](#)
[Molar Heat Capacities](#)

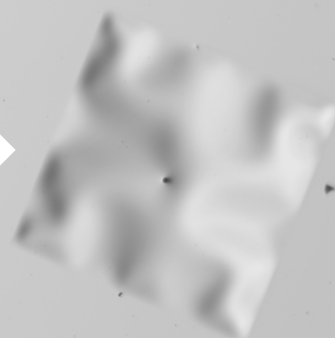


SEEING WITH ²He ATOMS

Creating the Beam



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	Electromagnetic waves	$v = f\lambda$	Magnification	$\frac{H_{image}}{H_{object}}$	Ray Diagrams	
A Level Physics	Electromagnetic waves	$v = f\lambda$	Magnification	$m = \frac{v}{u}$	Lens maker's equation	$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$


Introduction & context

The source of helium atoms that produces the helium atom beam source is approximately 100 μm across. A source this broad would only allow us to image details of a similar size. To improve the resolution of the instrument, the principles of geometric optics and the pinhole camera can be applied.

Reminder on beam formation


The beam for the helium microscope is formed from the expansion of helium gas into a vacuum chamber. A skimmer then selects the narrow beam of particles that are travelling in straight lines, at high speed in the forward direction. The result is that we obtain a source of helium that is typically about 100 μm across (about the width of a human hair). If we were to scan this beam across the sample the image that we would produce would have a resolution of about 100 μm . A pinhole that is much smaller than the source is placed in the path of the source beam.





Related Concepts

[Ray Diagrams](#)



Related Questions

[Multi-coloured Pinhole](#)

Pinhole optics

The pinhole currently about 1 μm in diameter. Such a pinhole produces two effects, it only allows a narrow beam of atoms through (those that travel approximately parallel to each other) and gives a demagnified image of the source (reduces its width) at the sample.

When the pinhole is large, many atoms pass through the pinhole and reach the sample, which would give a bright image but with low resolution. When the pinhole is small the beam that is directed at the sample has a much reduced width (illustrated as a radius r in this diagram), giving a higher resolution image but many fewer particles pass through making the image darker.

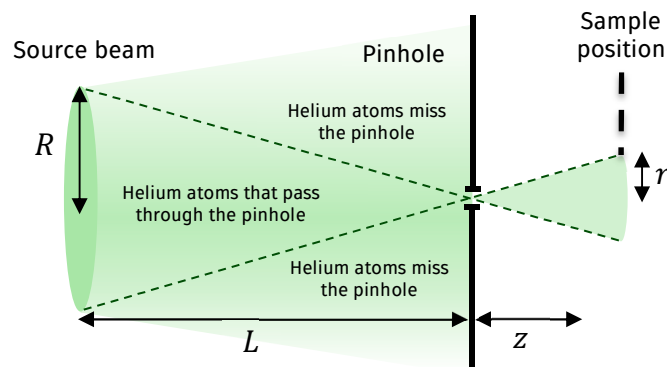


Diagram showing how the atom beam source is demagnified using a pinhole.

By adjusting the size and position of the source, and the size of the pinhole, the number of atoms that reach the sample can be optimised so that the image does not appear grainy (noisy). This graininess can be seen when taking ordinary photographs, if there is little light when the photograph is taken, too few light particles (photons) reach the camera and the image appears grainy.

The size of the demagnified beam depends on how far away the source is from the pinhole and how far away the pinhole is from the sample geometry and similar triangles.

$$\frac{r}{R} = \frac{f}{L}$$

Therefore

$$r = \frac{Rf}{L}$$

In the Cambridge SHem,

$$L = 200 \text{ mm}, R = 50 \text{ }\mu\text{m}, f = 2 \text{ mm}$$

which gives a demagnified beam of radius $r = 0.5 \text{ }\mu\text{m}$. By moving the source further away (increasing L), the beam can be made narrower but the number of atoms in the beam goes down.

Pinhole camera

The pinhole for demagnification in the SHem operates in a similar way to a pinhole camera. By using a short distance between the pinhole camera and the screen, large objects can be imaged onto small screens. Along with this leaflet you will find everything you need to make your own pinhole camera. Once you have made your pinhole camera you can experiment with how your image is affected when you change the distance from the pinhole to the object (source) that you are looking at. You can also investigate what happens to the image as you make the pinhole larger.

When designing a pinhole camera, many of the decisions that you have to make are similar to those decisions that we need to make for the SHem pinhole. If the pinhole is too small, the image is sharp but will be dark unless the object is brightly lit (need lots of light particles - photons in the same way that we need lots of helium atoms to make a clear image). If the pinhole is too large then plenty of light from the object reaches the screen but the object is now blurred and there is little contrast between the background light level and what you want to see.

The optimal pinhole diameter for a pinhole camera can be calculated using the formula

$$d = 2\sqrt{f\lambda}$$

where d is the diameter of the pinhole, f is the focal length of the camera (which is equal to the distance from the pinhole to the screen) and λ is the wavelength of light. So, if we use a camera that is a 20 cm cube, with visible light ($\lambda = 500 \text{ nm}$), then the size of the pinhole that we should use is approximately 0.6 mm.

Conclusion

Helium is difficult to manipulate because it is neutral and unreactive and so we are unable to use conventional techniques such as lenses to focus beams of helium atoms. However, it is possible to use simpler historical methods, very similar to those used in pinhole cameras, to produce a helium beam fit for purpose.

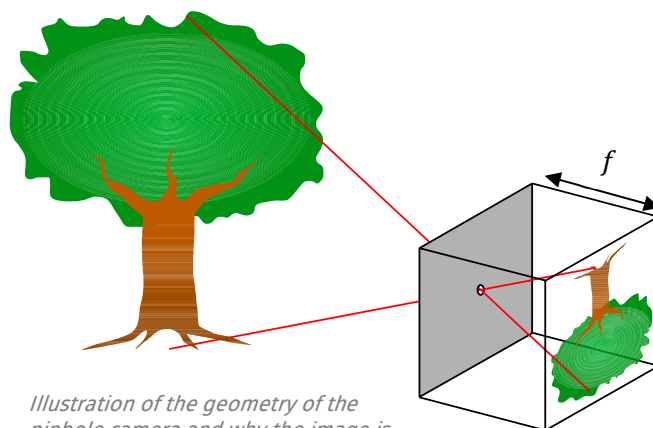
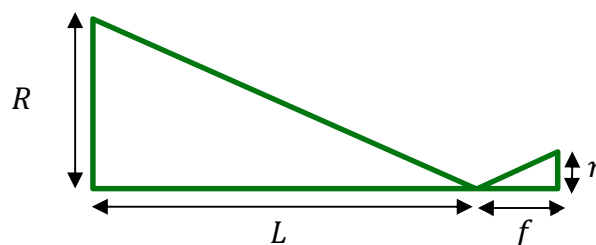


Illustration of the geometry of the pinhole camera and why the image is inverted Credit: From Wikimedia Commons



Related Concepts

[GCSE Book Section 48 – Convex Lenses](#)



Related Questions

[GCSE Book Section 48 – Q1](#)

[Out of the Shadows](#)

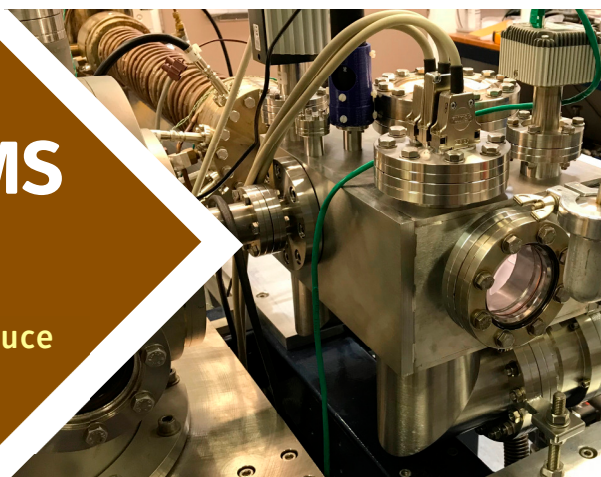
[Compound Microscope](#)



SEEING WITH ²He ATOMS

Contrast

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

Electromagnetic Spectrum

$$v = f\lambda$$

Law of reflection

$$\theta_i = \theta_f$$

A Level Physics

Wave particle duality

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

Introduction & context:



Photograph of a microwave oven
Credit: S. Schulze

When taking an image of an object with a camera, the way that light reflects off the object and reaches the film or CCD is important to give good contrast in the image. A smooth, mirror-like surface will reflect light brightly where the angle of reflection is equal to the angle of incidence.

A rough surface reflects light at a range of angles (known as diffuse reflection). For helium, making a smooth mirror like surface to produce a good contrast image would be incredibly difficult because almost all surfaces appear rough to helium atoms.

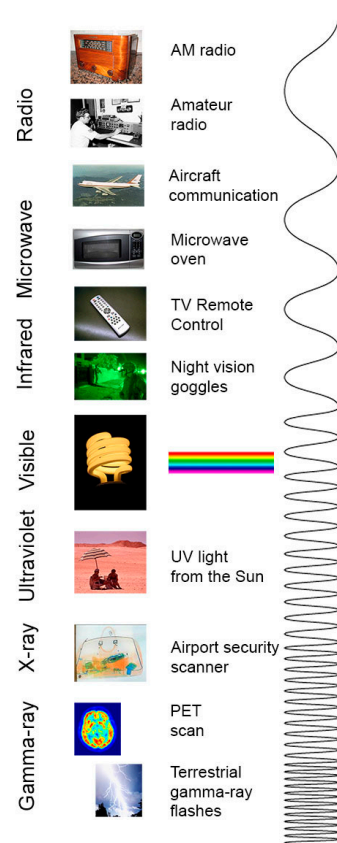
Why is this?

Microwave shielding

We can watch our food cook inside a microwave, but the microwaves cannot escape the oven to harm you, even though both microwaves and visible light are part of the same electromagnetic spectrum. Why can visible light escape but microwaves not? In answering this question, we will also understand why surfaces appear rough to helium, even if they appear shiny and flat when viewed by eye.

The wavelength of visible light is about 500 nm, but the wavelength of a microwave used for cooking is about 120 mm. The shielding in a microwave door has holes that are about 1 mm in diameter, which means that it appears reflective to a microwave. However, the wavelength of visible light is typically $1/2000$ of the hole diameter, so visible light can pass through the holes and we can still see inside the microwave oven and watch our food being cooked!

This analogy helps us to understand that electromagnetic waves of different wavelengths respond differently to material structures (e.g. the holes) **because of the relative size of those structures compared with the wavelength of the light.**



Credit: NASA's Imagine the Universe



Related Concepts

Electromagnetic waves



Related Questions

EM Frequencies



Law of reflection

For a surface to behave as a mirror for visible light it must be reflective and much flatter than 500 nm, whereas a mirror for microwaves only needs to be significantly flatter than 120 mm. By flat, we mean that any surface structures (bumps or dips) must be much smaller than the wavelength of the light.

If a ray of light is incident on a mirror, then the reflected light will follow the law of reflection such that the incoming angle of the ray is equal to the outgoing angle of the ray.

$$\theta_i = \theta_f$$

The reflective surface will obey this law, and behave as a mirror, if the surface is flat compared with the wavelength of the incoming light.

Helium scattering

From wave-particle duality we can calculate that the helium beam in the microscope has a wavelength of 0.05 nm, which is $1/10,000$ of the wavelength for visible light. Therefore, most materials look rough to the helium beam, even surfaces that appear shiny to the eye.

For a material to act as a mirror for a helium beam, it would need to be atomically flat (10^{-10} m). The samples that we wish to investigate are not this smooth and the helium is scattered diffusely in all directions from their surfaces.

However, most of the helium is scattered perpendicular to the surface and the brightest part of an image is where the normal to the surface is pointing towards the detector. For example, in this image of a glass microsphere (~0.4 mm diameter) on the edge of an adhesive carbon tape, the left hand side of the sphere is pointing towards the detector.

In images produced using the helium microscope, brightness is determined by the number of atoms that reach the detector. The more atoms that are counted by the detector the brighter the pixel in the image. If no atoms reach the detector then the pixel in the image appears dark.

Result – Contrast

Helium beams scatter diffusely from most surfaces due to the wavelength of the beam being so small that most surfaces appear rough. Understanding how helium atoms will scatter from a surface enables us to maximize the contrast in our images. We want to make bright areas of the image as bright as possible and dark areas as dark as possible (i.e. maximize contrast) so that we can identify features in the sample that may help us to understand its structure or physical properties.

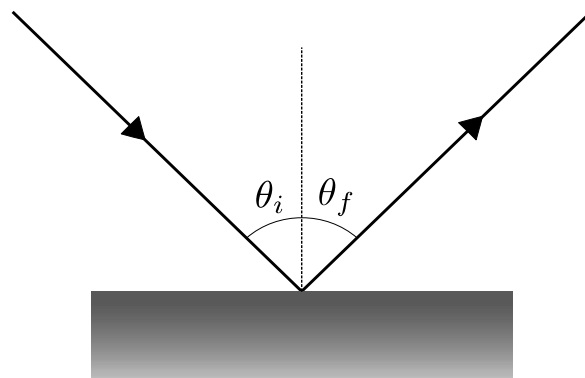


Diagram illustrating the law of reflection, angle of incidence = angle of reflection

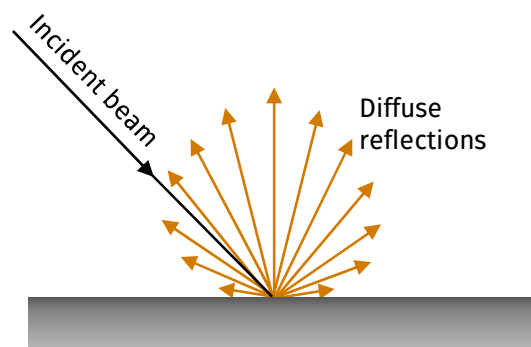
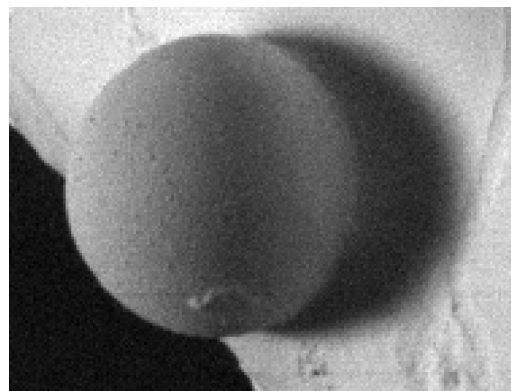


Diagram showing diffuse reflection from "rough" surfaces



Scanning helium microscope image of a glass sphere (~0.4 mm diameter) with a coating of gold, on the edge of an adhesive carbon tape. Credit: Cambridge surface physics group



Related Concepts

GCSE Book Section 39 – waves – plane mirrors

Waves

Reflection and Refraction



Related Questions

Essential GCSE Physics 39.1

Light on Surfaces

Seeing Double

Cat's Eye



SEEING WITH ²He ATOMS

Creating an Image

4.0026

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	Lorentz Force ¹	$F = IlB$	Newton's Second Law	$F = ma$	Ionisation	${}^4_2\text{He} + e^- \rightarrow {}^4_2\text{He}^+ + 2e^-$
A Level Physics	Lorentz Force ¹	$F = qvB$	Newton's Second Law	$F = ma$	Circular Motion	$a = \frac{mv^2}{r}$

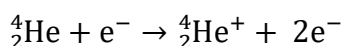
Introduction & context

How is it possible to measure how many helium atoms are scattered from a surface, given that they are neutral and unreactive? The pressure of helium that is being measured is typically about more than 10^{15} times lower than atmospheric pressure, so a standard mechanical pressure gauge will not be sensitive enough and a much more sensitive gauge is needed.

Ionisation

Detectors in *electron* microscopes are able to measure the number of particles because the *electrons* have a charge and therefore interact with electric and magnetic fields. To use similar techniques in a helium microscope, we need to ionise the neutral helium atoms. When the particle is charged we can measure the number of ions per second (ion current).

The helium atoms are ionised with a beam of high energy electrons that is directed into the gas (electron ionisation). When high energy electrons collide with a helium atom, one of the electrons in the helium's outer shell is removed, forming a helium ion.



Mass filtering

The vacuum chamber does also include some other contaminant gases (e.g. hydrogen) and unfortunately, the electrons also ionize these gases creating other positively charged ions. We want to count the current of positive helium ions only and therefore need to separate these from the large number of other positive ions.



Related Questions

[Ionisation Energy](#)



¹ The Lorentz force is the force on a moving charge, or current carrying wire, in a magnetic field.

A magnetic field can be used to select ions with a specific mass-to-charge ratio (as in a mass spectrometer) because a moving charged particle in a magnetic field experiences a force, the Lorentz force. The size of the Lorentz force, F , is given by

$$F = qvB$$

where q is the charge of the ion, v is the velocity of the ion and B is the magnetic field strength in the region.

The direction of the Lorentz force is always perpendicular to the velocity of the ion, which means that the Lorentz force acts as a centripetal force and causes the ion to move in a circle. The radius of this circle will depend on the mass of the ion and its charge. Using Newton's Second Law, we can calculate the radius of the circle

$$\begin{aligned} F &= ma \\ qvB &= m \frac{v^2}{r} \\ r &= \frac{m v}{q B} \end{aligned}$$

where, m is the mass of the ion and r is the radius of the circle.

From this relationship, we can see that if the ion has a larger mass-to-charge ratio then the radius of the circle will be larger. Therefore, provided that the positive ions all reach the magnetic field with the same velocity, then they will be separated depending on their mass-to-charge ratio.



For example, hydrogen gas becomes H_2^+ which has a mass of $2m_u$ and a charge of $1e$. The helium ions however have a mass of $4m_u$ and $1e$. The radius of the helium arc is therefore twice as large as for the hydrogen arc. Some ions are multiply ionised, although not usually helium.

So, in the helium microscope the mixed ion beam is fed into a uniform magnetic field, with the velocity perpendicular to the magnetic field direction. The ions then exit the magnetic field travelling in the opposite direction. All ions entered the magnetic field at the same point but now the exit position of the different ions is separated according to their mass-to-charge ratio.

By placing a small hole at the output from the magnetic field, it is then possible to select one specific mass to charge ratio, which for He^+ is a ratio of $m/q = 4$ (where m is in units of $m_u = 1.66 \times 10^{-27} \text{ kg}$ and q is in units of electron charge, $e = 1.60 \times 10^{-19} \text{ C}$).

Creating the image?

Using a mass spectrometer to separate out the helium ions enables us to count the number of atoms per second that have been scattered by our sample. The count is then passed to the control computer which generates an image where the brightness of a pixel in the image is based on the number count – the more counts the brighter the pixel.



Related Concepts

[Magnetic Fields](#)

[Lorentz Force](#)

[GCSE Book Section 18: Moving in a Circle](#)

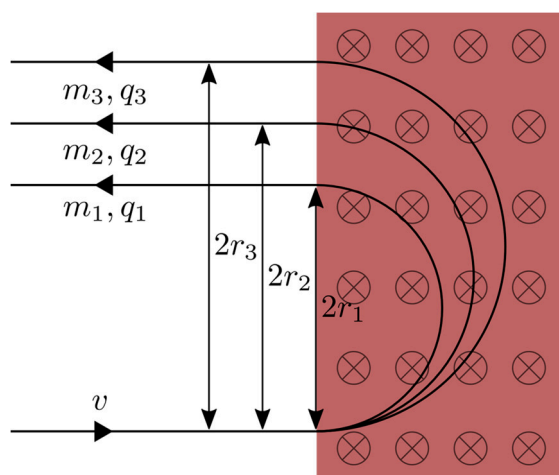
[Circular Motion](#)



Related Questions

[Starting with the Basics](#)

[A Mass Spectrometer](#)



Uniform magnetic field
(into the page)

Diagram showing the deflection of ions in a uniform magnetic field that is perpendicular to the direction of motion of the ion. The ion experiences a centripetal force due to the magnetic field and undergoes circular motion with a radius determined by the mass to charge ratio of the ion.



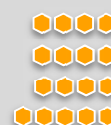
Related Questions

[Deflecting Ions](#)

[Deflection of a Charged Particle](#)

[Electron in a Magnetic Field](#)

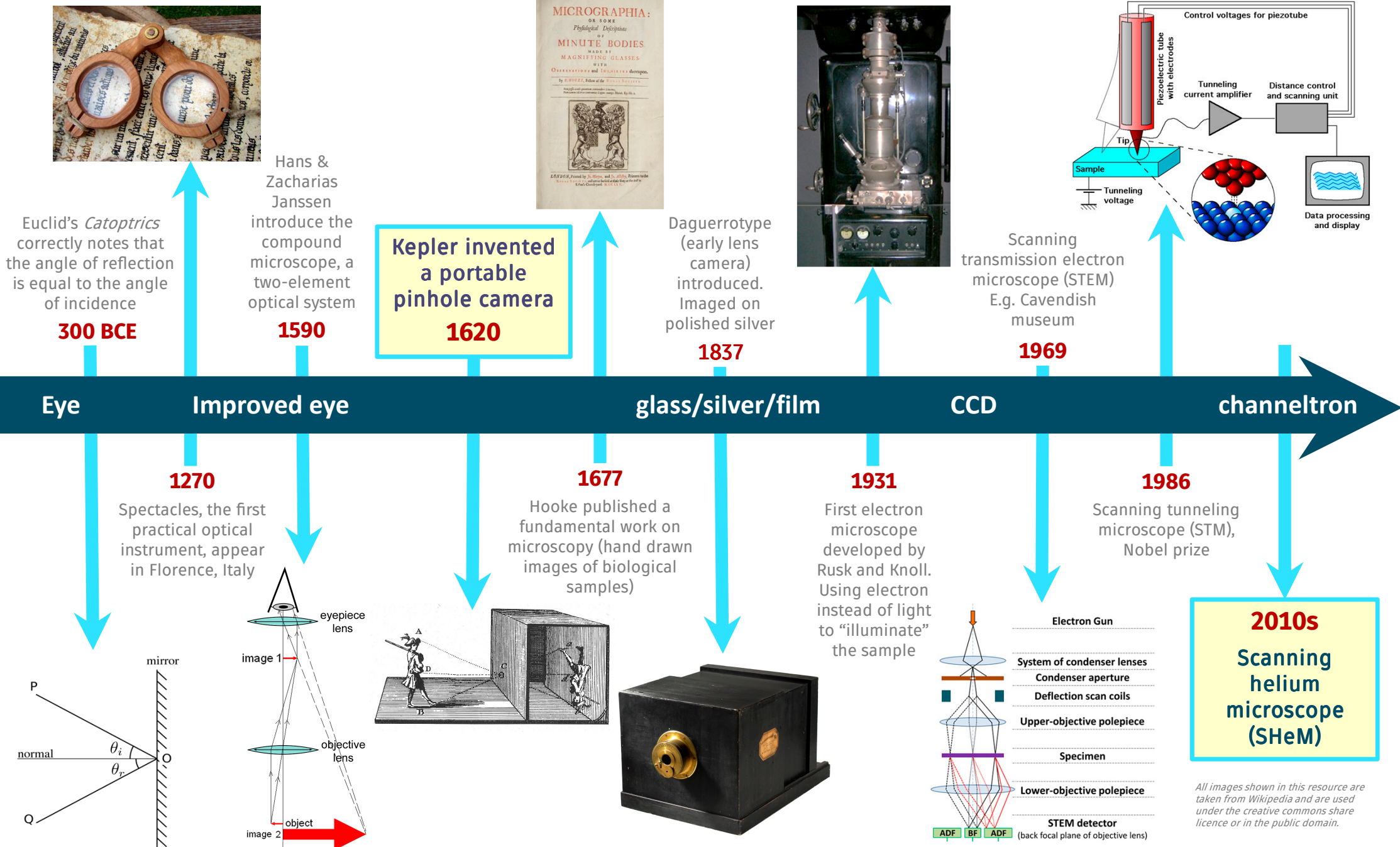
[A Charge in a Magnetic Field](#)



SEEING WITH ²He ATOMS

4.0026

A brief guide to the history of imaging and microscopy

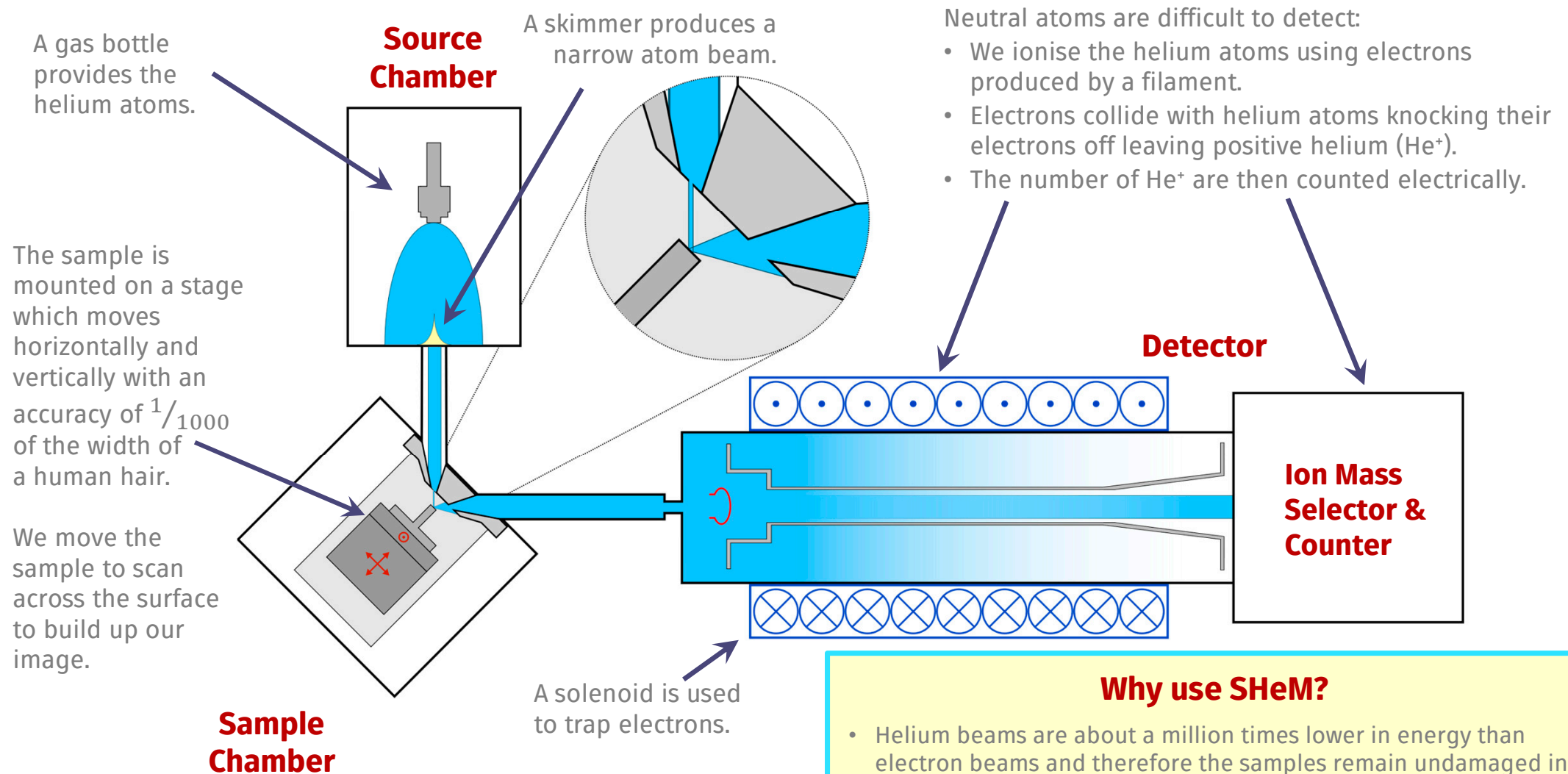


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What is scanning helium microscopy?



Credit: Matthew Bergin, Cavendish Laboratory

This diagram shows the basic layout of the SHeM.

All apparatus from the sample chamber onwards operate in a vacuum, with fewer particles per square meter than in outer space

Why use SHeM?

- Helium beams are about a million times lower in energy than electron beams and therefore the samples remain undamaged in SHeM imaging.
- With electrons, charging of the sample surface can cause images to blur - helium is uncharged and so SHeM images remain clear.
- No sample preparation is required in SHeM, whereas in EM imaging many insulating samples must be coated with a metal, changing their properties.
- SHeM images have a large depth of field (high range in focus).