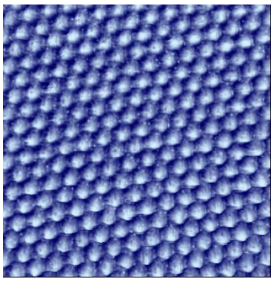
Bridge between research in modern physics
and entrepreneurship in nanotechnology

# Quantum Physics

*The physics of the very small*
*with great applications*

## Part 2

## QUANTUM PROPERTIES & TECHNOLOGY



## Learning Station VIII:
## **Tunnelling & STM**



Lifelong Learning Programme

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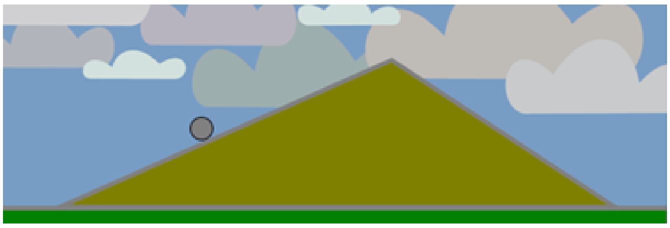
# Learning station VIII: Tunnelling & STM

## 1 Over a potential barrier without the needed energy

### 1.a Classical particles cannot tunnel



(Source: Concord.org)

If you want a ball to roll over a hill top, you need to give it enough (kinetic) energy to overcome the barrier of potential energy which is formed by the hill.

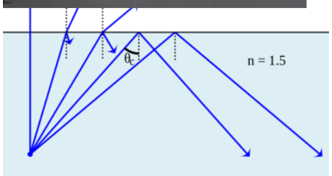
1. If it does not have enough energy, it (will/will not) pass the top
2. If it does have enough energy, it (will/will not) pass the top

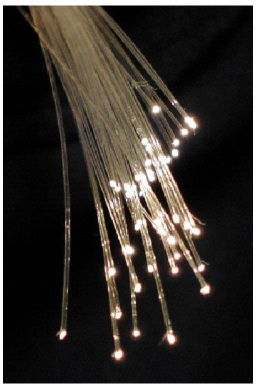
The strange thing is that unlike macroscopic balls, *quantum particles,* like electrons and photons (particles of light) may indeed pass a barrier, even though they might not have the needed energy. In fact quantum physics predict a chance for quantum object to tunnel through an energy barrier depending on the particle's energy and the height and width of the barrier.

### 1.b Light can tunnel through a barrier

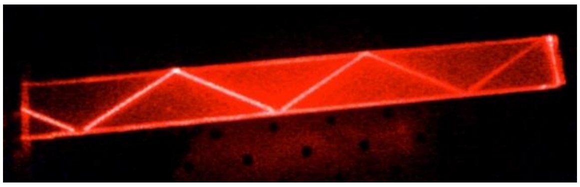
As you remember, light rays going from an optically dense medium to an optically thin one can be totally reflected or transmitted. The effect is due to the changing velocity of light which is (slower/faster) in the dense medium than it is in the thin.

If the angle of incidence is larger than a certain critical angle, which depends on the relative refractive index, the light is totally reflected by the optically dense medium.



(Source: Wikipedia public domain)

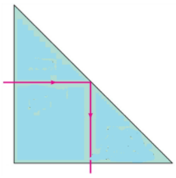


This makes it possible for light to stay in an optical fibre. Thus light cannot come out of the dense medium once the angle of incidence is large enough.

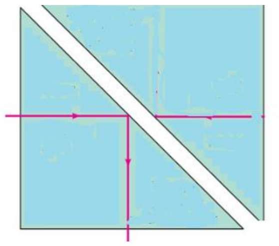
Frustrated Total Internal Reflection

But the effect of tunnelling makes it now possible for light to overcome this not to exceed barrier. We can show this in an experiment with two prisms. You can watch this experiment on http://www.youtube.com/watch?v=aC-4iSD2aRA

**Experiment: frustrated total internal reflection with light**



As an example let us consider shining a laser beam on one side of a prism as on the figure. On the other side the angle of incidence is large enough to get total internal reflection: the light cannot leave the medium.



But then we approach with a second prism. When we press the second prism to the first (if necessary you can wet the sides with water) at once the light can leave the first prism and make it to the second prism although it is classically forbidden to overcome this gap.

A classical particle cannot know that you are holding a second prism nearby. It is because of the quantum wave character of light that it can penetrate the gap and has a chance to tunnel through the gap.

**Experiment: frustrated total internal reflection with microwave**

The gap between the prisms should be of the order of the wavelength of light. For red light this is about 600 nm. This means the two prisms should be very close to each other. For microwaves, who have wavelengths in the order of centimeters, it can be shown that a gap of a few centimeters is already enough to get tunneling.

You can look at an experimental implementation of microwave tunnelling at http://www.sixtysymbols.com/videos/reflection.htm

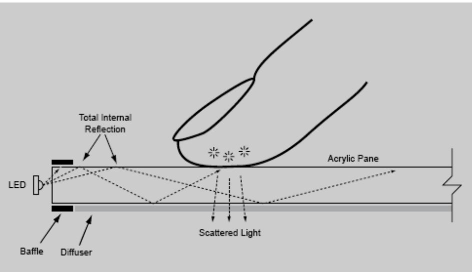
(Source: University of Nottingham)

## 1.c Tunnelling in daily life

When a glass of water is held, you can't see your fingers due to the total internal reflection of light in water.

But what happens when you press your fingers firmly to the glass?

The effect is very similar to the experiment with the prism described above: the ridges in your skin are becoming visible because the light tunnels through the gap. Light tunnels from the glass into the ridges through the very short (air) gap that forms when you press (Source Wikpedia public domain)




This tunnelling effect with light (breaking total internal reflection), can be used to make a touch screen: by means of a light sensitive cell, one can detect the reflected light and detect where your finger is on the screen.

(Source: New York University: cs.nyu.edu/~jhan/ftirsense/ )

# 2 Tunnelling: a characteristic of waves

Let us explain this phenomenon of tunnelling.

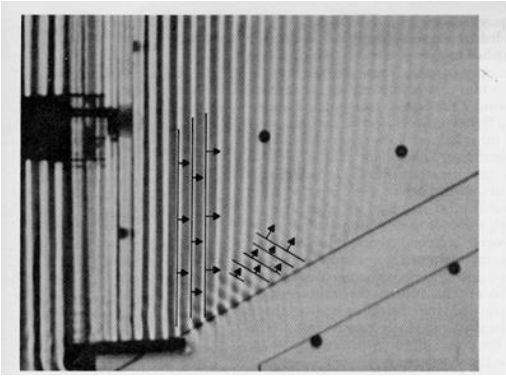
**Frustrated total internal reflection: Explanation by tunnelling**

As long as the light is totally in the glass it cannot 'know' what is beyond the glass. To find out it has to penetrate a short distance into the forbidden zone, perhaps a few wavelengths. If a second piece of glass is placed within the penetration distance, the beam can reappear. The probability to penetrate the air gap decreases as the thickness of the barrier increases.

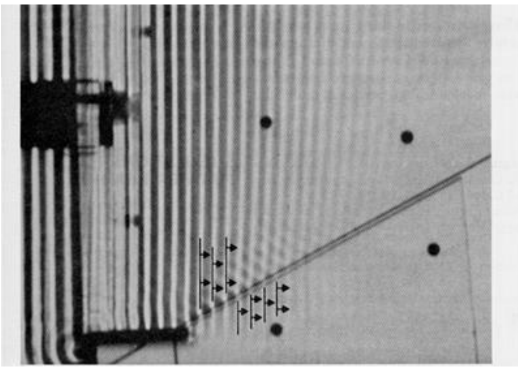
**Tunnelling of water waves**

The total internal reflection is caused by a sudden change in the propagation velocity of light at the boundary. For example in glass the speed of light is much (slower/faster) then in air.

The speed of water waves is also dependent *on the depth* of the water. In shallow water the velocity of the waves is slower whereas in deep water the water waves propagate faster. Therefore with water waves you can also see the phenomenon of total internal reflection as it is seen with light in matter.

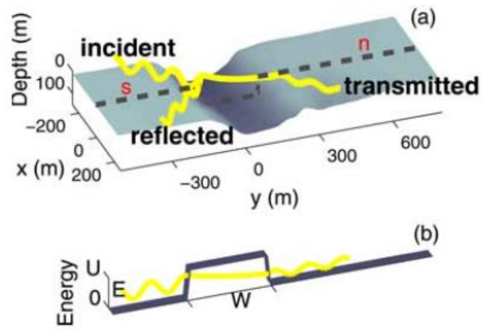


The two slope lines mark a zone where the water is deeper. The waves which are coming from the left, are reflected on this deep zone.



When the gap created by the deep water is made sufficiently narrow (of the order of magnitude of the waves themselves) suddenly the waves can tunnel through the gap and are (partially) transmitted across.

Source Education Development Center, Newton, MA USA




The tunnelling of waves is also observed with ocean waves above sea bottom canyons!

Thomson, J., Elgar, S., & Herbers, T. H. C. (2005). Reflection and tunneling of ocean waves observed at a submarine canyon. *Geophysical research letters*, *32*(10).

# 3 Electrons may tunnel too

Since we know that light *and matter* both have this particle-wave duality, tunnelling is not only possible for photons but it is possible for electrons too.

Precisely quantum physics describes this wave character of electrons. Electron waves can tunnel through a classically impenetrable barrier.

So for quantum physics it is natural that also electrons can tunnel through a barrier although they do not have enough energy to overcome that barrier.

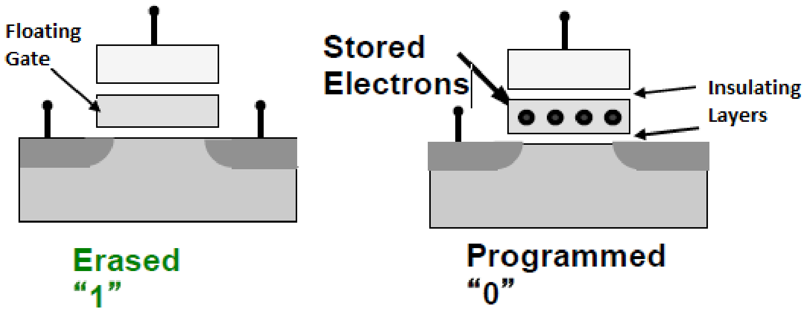
## 3.a An application: Flash Memory

A nice application based on electron tunnelling is flash memory that is used in usb sticks, on smart cards and the like. It will maintain its data without any external source of power.

It is based on electron storage. Electrons are stored in a so called Floating Gate that is *isolated from the rest of the device* by insulating oxide layers: **any electrons placed on it get trapped there and thus store the information**.

The electrons are tunnelled through the insulating layer and trapped in the Floating Gate. After the tunnelling the barrier should be made thick enough to keep them there for many years.

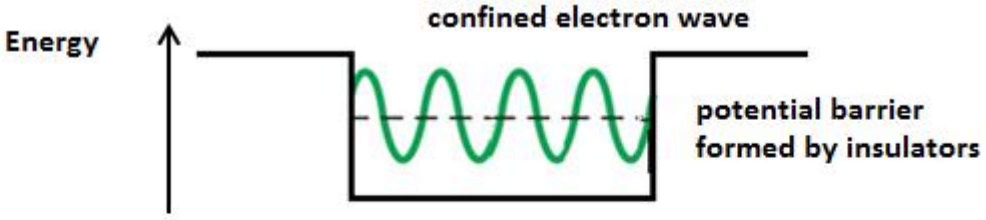
The tunnelling of electrons through a (electric) potential barrier can be understood by the the wave character of the electron, an assumption that is made in quantum physics.



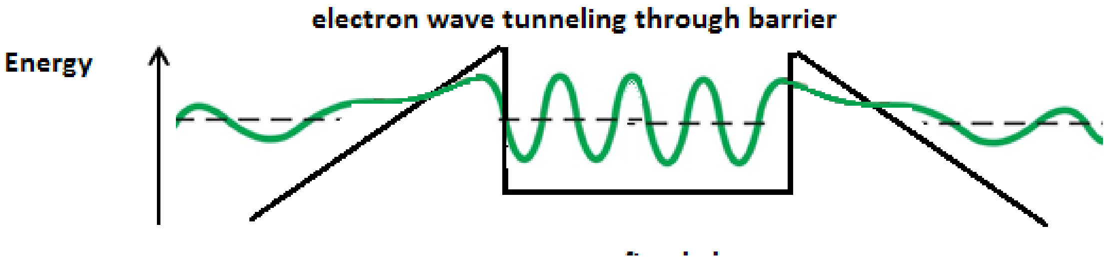

Source: Massachusetts Institute of Technology Open Course Ware

## 3.b Flash Memory explained by tunnelling of electron waves

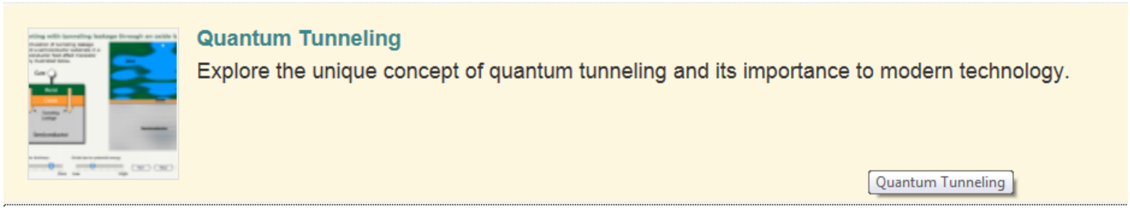
The surrounding insulating layers confine the electron in the energy well where it can stay for many years without external power source. This is the basis for the non-volatile storage.




By applying an electric field over the gate, the potential barriers can be made thinner, so the electron can tunnel out of the gate or into it again. Tunnelling makes it possible to write zeros or ones into the gate.




You can find **more learning materials on tunnelling and a simulation of the working of the flash memory on concord.org**




*Simulations of Quantum Tunnelling on Concord.org*

## 3.c Tunnelling underlies many processes

It becomes more and more clear that quantum tunnelling plays an important role in chemistry, and also in the chemistry of life[1]. In the photosynthetic process for instance electrons tunnel from one molecule to another, penetrate membranes and the like and therefore make fast energy transfer processes possible. Research in this area has opened up many possibilities in the emerging field of quantum biology, and this may even shed light on a method towards developing more efficient solar cells.

Also processes like radioactive αlpha-decay can only be understood in terms of tunnelling: in this case it is a nucleus of He that tunnels out of a bigger atomic nucleus. The pure stochastic nature of radioactive processes is of course to be understood as a consequence of the quantum character of particles. The probabilistic character of nature, which can be seen at nano level, is explained by the wave-particle duality. The amplitudes of the quantum mechanical waves are proportional to the probability of measuring a quantum of energy (a particle) at different places.

In electronic circuits, the conductive areas (formed by metals) in which electrons move are separated by insulating layers in which electrons are classically prohibited. These insulating areas act as barriers to free electrons so that they can move only within the conductive areas. In early circuits, the barriers were very thick, making electron tunnelling negligible. However, when the barriers get *thinner/thikker*, tunnelling becomes significant and the barriers lose part of their confining function. This is a problem for further

[1] See for instance: Moser, C. C., Keske, J. M., Warncke, K., Farid, R. S., & Dutton, P. L. (1992). Nature of biological electron transfer. *Nature*, *355*(6363), 796-802.

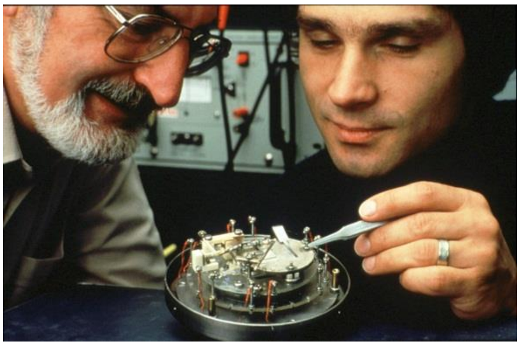
miniaturisation of circuits. On the other hand, tunnelling gives new opportunities for new applications

In fact, *trillions of tunnelling events occur while you are reading this page both in nature as well as in technology*. Tunnelling is a property of nature that nano scientists and engineers need to understand further.

A fascinating application of electron tunnelling is the development of the Scanning Tunnelling Microscope: a device that made it possible to peek into the atomic, even subatomic scale.

# 4 Scanning Tunnelling Microscopy (STM)

## 4.a Scanning tunnelling microscopy (STM)



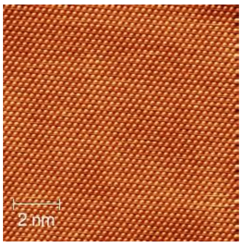
The Scanning Tunnelling Microscope was developed in 1982 in Switzerland by the IBM research laboratory in Rüschlikon and awarded the Nobel prize for physics in 1986. The STM made it possible for the first time to "see" or "scan" atoms. The necessary technical and physical conditions will be discussed below.

*Heinrich Rohrer and Gerd Binnig with their first scanning tunnelling microscope (source: IBM)*

**Utilizing the nature of waves**

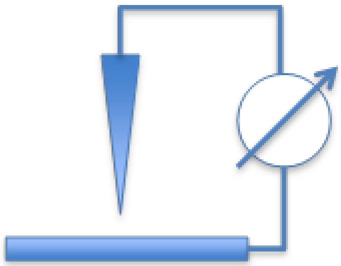
Quantum mechanics teaches that electrons do not move in the atom like small spheres on trajectories but stay somehow "blurry" in areas – i.e. the orbitals we talked about at the end of learning station V. This is a consequence of the wave nature of electrons. In a nuclear structure, e.g. a metal, *there is a small probability that electrons may also be present slightly outside the surface*, something not possible in accordance with classical physics. If you move a measuring probe close enough to this metal surface, a small electrical current can be measured. It actually looks as if the atoms were "tunnelling" through this gap or energy barrier. Therefore, this effect is also called the "tunnel effect".

*The scanning tunnelling microscope of NanoSurf*




*STM picture: Atomic structure of silver (Ag(111)).*

*(source: University of Basel, Department of Physics)*




Since the electrons are only just above the surface – *at a distance of 1-2 atom diameters* – the measuring probe must be moved very close and precisely to the surface. This was already known in the 1950s, but it was unclear how it could be technically implemented. Only in 1982 did Gerd Binnig and Heinrich Rohrer implement this with a device called the scanning tunnelling microscope.

***Task 4.1:***

*Try to depict the influences which get in the way if a probe needs to be positioned at a distance of an atom (~0.1 nm) above a surface.*

**Functional principle of the STM:**

The scanning tunnelling microscope is based on measuring the **tunnel current** at the surface of the sample. To this end a platinum or tungsten probe is used which scans surfaces with a defined tunnel current. The positioning mechanism guides the probe over the surface in such a manner that always the same current is measured. The tracking movements[2] are recorded and return an image of the surface.

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[2] The movement of the probe along the surface or the correcting variable of the corresponding piezoelectric actuators in the x/y axis (see Fig. 4.1)

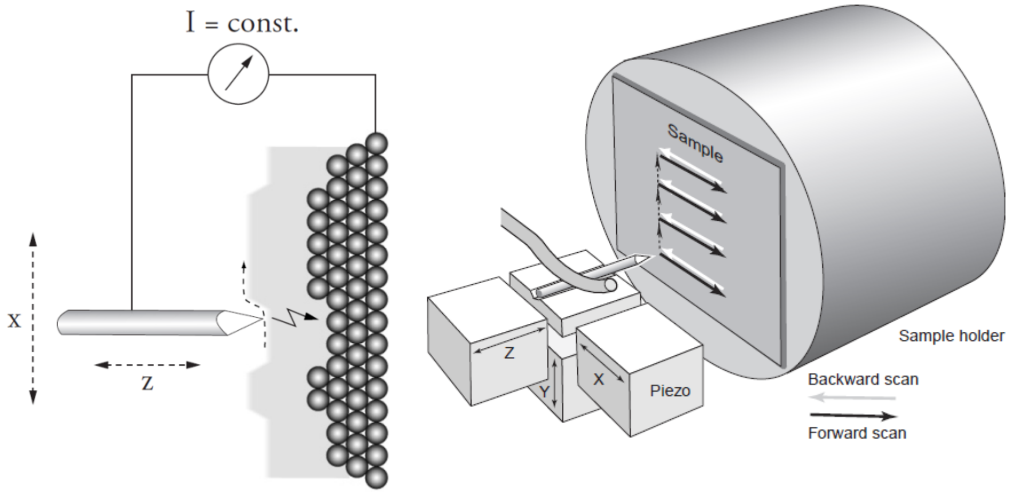



**Figure 4.1:** Functional principle of the STM

Suitable for these tricky positioning tasks are so-called piezoelectric crystals, e.g. quartz or lead zirconium titanate. These feature (minimal) expansion when an electrical voltage is applied. Conversely, they generate a voltage if they are compressed.

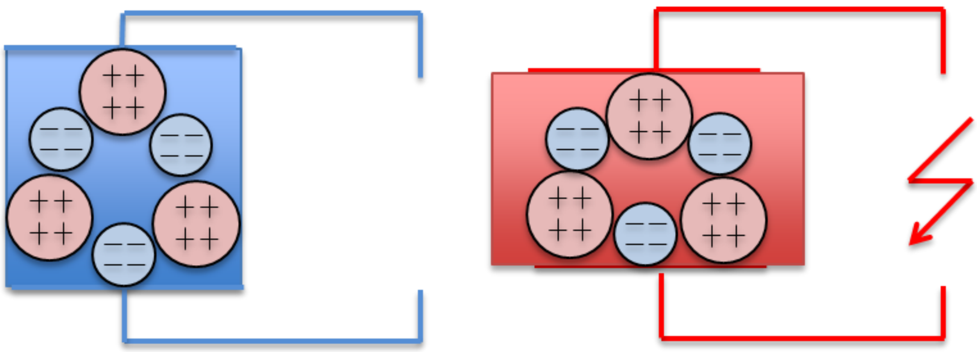
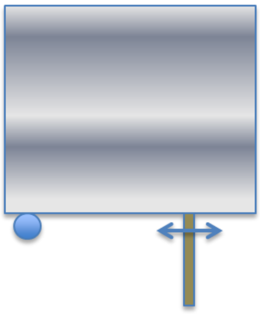


**Figure 4.2:** Functional principle of a piezoelectric crystal, i.e. crystals which acquire a charge when compressed, twisted or distorted. By squeezing a piezoelectric crystal we generate an electrical voltage and thus we can make electricity flow through it by connecting the two faces together to make a circuit (right figure). The reversed process is shown in the left figure: the crystal becomes mechanically stressed (deformed in shape) when a voltage is applied across its opposite faces.

***Task 4.2:***

*Where do we find piezoelectric crystals in daily life?*

The next technical challenge in the construction of an STM is the approach of the probe to the surface of the sample to be measured. Elaborate precision micrometre screws with step motor actuator or simple piezoelectric step motors can be used for this purpose.



The working principle is the following: we need a cylinder resting on a support (blue) and a movable piezoelectric crystal lamella (green) which can be moved for- and backward using an electrical voltage. If the lamella is moved slowly to the right, the cylinder can follow the movement; if the lamella is moved quickly to the right, the cylinder cannot keep up due to its inertia and stays behind. If you repeat this process, the cylinder moves to the right.

With this kind of motor steps of 50-100 nanometre can be achieved allowing a sample to be moved within the control range of the measuring probe.

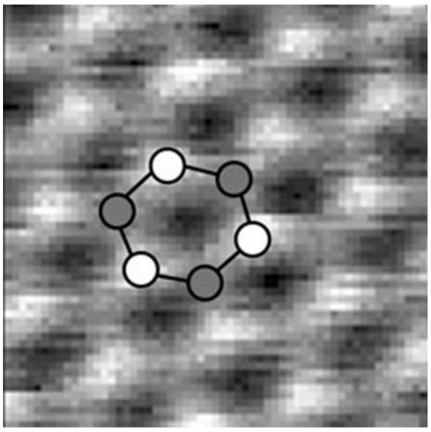
***Task 4.3: Temperature sensitivity:***

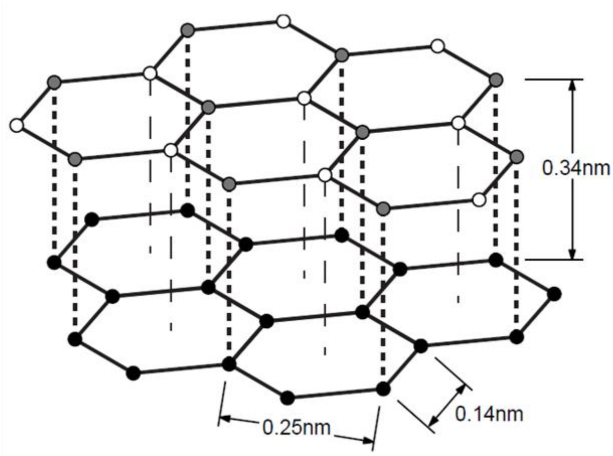
*Calculate how much the cylinder expands with one Kelvin of heating.*

*Cylinder length 2.5 cm, expansion coefficient for iron:* $\alpha = 11.8 \cdot 10^{-6}\ K^{-1}$.

*What measures must therefore be taken for smooth operations?*

The scanning tunnelling microscope does not only measure the shape of the surface but at the same time the electrical conductivity near the sample surface. If a higher current is measured at a location this may also be due to the electrons being less strongly attached to the atoms there than at other locations. This effect can be seen when measuring graphite.



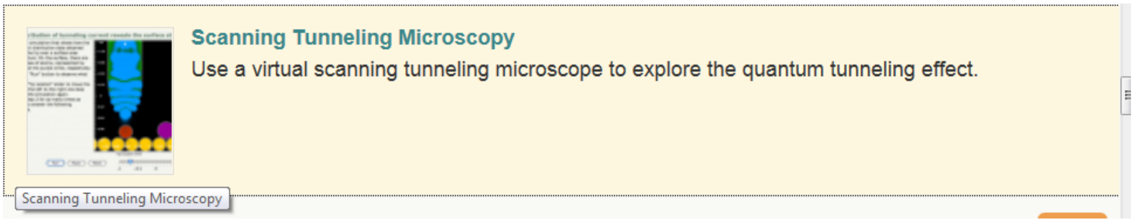



On the left you see a measurement of the atomic lattice of a graphite surface – however, you cannot see the hexagonal structure of the lattice known from scattering experiments. It seems we can only see every 2nd carbon atom in the STM image.

***Task 4.4:***

*Given the structure of the graphite layers, how do you explain that only every 2nd atom is visible?*

**More learning materials on the scanning microscope can be found at concord.org**




*STM simulations at Concord.org*

**Solutions:**

**4.1:**

Vibration, thermal expansion

**4.2:**

Piezoelectric loudspeaker, oscillating quartz in watches and radios, piezo igniter[3]

**4.3:**

$\Delta L \approx \alpha \cdot L_0 \cdot \Delta T$ = 295 nm. The scanning tunnelling microscope measures in the nanometre range and the expansion is several hundreds of nanometres, significantly distorting the measurement. Measures must be taken for thermal stabilisation, such as draught shielding using a hood, avoiding a direct heating light source or allowing sufficient time for stabilisation.

**4.4:**

There are 2 different positions in the graphite lattice: the "grey" ones with a neighbour in the lower lattice level – the electrons of these atoms interact with the atoms of the underlying layer and are therefore more strongly attached. The "white" atoms do not have a neighbour in the underlying level and can more easily release electrons and are therefore more clearly visible.

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[3] Piezo igniters are used in gas grills or lighters.

# 5 Concepts in Learning Station VIII

**Complete by adding the missing concepts**

### Classical concepts

Macroscopic objects can only overcome a barrier of potential energy if they have ………………………………………

Total internal reflection occurs for light .............. going from an optically .............. medium to an optically ............... one when the angle of incidence is ............... than a critical angle.

The same effect can be observed with water waves as the speed of water waves depends on the ............... of the water. However when the gap created by the deep water is made sufficiently ............... - of the order of magnitude of the waves themselves - suddenly the waves can tunnel through the gap and are (partially) transmitted across.

### Quantum concepts

Particles can tunnel through an energy barrier due to their ..........................................

This is a quantistic effect because tunneling happens ..................................... – each photon has wave nature.

Due to their ……………………………………………………, electrons and matter in general can tunnel too. I.e. they can tunnel through an energy barrier though they do not have enough energy to overcome the barrier.

The chance for quantum objects to tunnel through an energy barrier depends on the particle's …………………………… and the …………………………………… of the barrier.