

Lesson Template

Subject Area(s) Physics

Associated Unit

Lesson Title Quantum Tunneling

Header Insert Image # or Figure # here [note position: left justified, centered or right justified]

blank

Yellow highlight = required component



Figure

ADA Description: Photo of Platform 9 three quarter at Kings Cross railway station.

Caption: Figure #. In Harry Potter young wizards must tunnel through a wall to get on the Hogwarts express train.

Image file: lesson_quantum_tunneling_fig_1_web_harrypotter.jpg

Source/Rights: Copyright © flickr. Franz St.
<http://www.flickr.com/photos/fstifter/2367190954/sizes/l/in/photostream/>

Grade Level 12 (12)

Lesson # ___ of ___

Lesson Dependency

Time Required 30

Summary

Students are introduced to the basic principles of the quantum mechanical phenomenon of tunneling. The students are introduced to the idea by relating it to Harry Potter. They learn about the scanning tunneling microscope as an application.

Engineering Connection

Engineering Category = #1

Choose the category that best describes this lesson's amount/depth of engineering content:

1. Relating science and/or math concept(s) to engineering
2. Engineering analysis or partial design
3. Engineering design process

Keywords

Quantum mechanics, tunneling, Harry Potter, nanotechnology

Educational Standards

Choose from <http://www.jesandco.org/asn/viewer/default.aspx>.

ITEEA (provide standard number, grade band, benchmark letter and text):

State/national science/math/technology (provide source, year, number[s] and text):

ITEEA, Standard 10, Grades 9-12, L. Many technological problems require a multidisciplinary approach.

Texas. Chapter 112 (Texas essential knowledge and skills for science, amended 2009). Subchapter C (High School). Physics. (8) Science concepts. (D) give examples of application of atomic and nuclear phenomena.

Pre-Requisite Knowledge

Before understanding scanning tunneling microscope, the students need to have a basic understanding of the atom structure, wave-particle duality, and electrons.

Learning Objectives

After this lesson, students should be able to:

- Understand difference between classical and quantum physics
- Understand and describe the basic idea of quantum mechanical tunneling
- Understand the basic principle of the scanning tunneling microscope

Introduction / Motivation

How many of you have read at least one Harry Potter book? (Expect many) Do you remember the name of the wizard school? (Take answer: Hogwarts) And how did they get there? (Hogwarts express) Do you remember the platform number and how they get on the Hogwarts express train? (Take answers. Show associated slide of platform 9 $\frac{3}{4}$. Young wizards must run very fast towards the brick wall and tunnel through the wall to get on the train. Show slide of the attached ppt presentation). That clearly seems like magic.

(Now, take a tennis ball in your hands). If I throw this tennis ball at the wall, it will bounce back. (Throw tennis ball at wall) If I throw it 100 or even 10,000 times, will it always bounce back? (Continue throwing tennis ball while talking) What happens if I throw very hard? (Take answers from students) The ball will always bounce back even if I throw it very hard.

However, in the world of atomic scale, it is possible that quantum objects go through barriers. Recall that the physics on the atomic or sub-atomic scale is called quantum physics or quantum mechanics.

Quantum tunneling is a unique phenomena resulting from the wave nature of a particle. (Show second slide of attached ppt presentation.) Recall that for an electron, the wavelength of the particle's wave function is inversely proportional to the momentum of the electron. Thus, when the particle's wavelength is large, its momentum is small, and vice versa.

Treating particles classically, like the tennis ball (Show tennis ball again), does not allow a particle to overcome a barrier like a wall. (Throw the tennis ball against the wall again.) However, we now know that particles also have a wave nature. The wave nature becomes especially important for very small particles, quantum particles. On the quantum level the physics is not described by Newton anymore. Strange things happen and the behavior is described by very mathematical quantum mechanics. Quantum mechanics allows for small particles to tunnel through a barrier from time to time. The phenomena is described in terms of probabilities and the although the probability for the particle to go through a barrier is small, it is not zero and happens. (Show third slide of the attached ppt presentation).

Now, how can we know that this happens? Where is that behavior observed? Can we even use it maybe? Well, without tunneling we would not even exist. The sun would not even exist as the reactions inside it rely on the principle on tunneling.

The principle is used also in technology. One technological challenge is to understand and assess nano-materials. Using the tunneling, engineers designed a microscope that allows imaging on the microscopic level. These microscopes are called scanning tunneling microscopes because they are based on quantum mechanical tunneling, as we will see. (Show slide with the concept of the scanning tunneling microscope.) The tip is brought very close to surface to be examined and a small voltage is applied. Now, electrons can tunnel through the gap resulting in a current. The current depends on the width on the gap. Using information about the current therefore allows to get information about the surface.

Understanding the surface on the microscopic scale is especially important in the field on nanotechnology. New materials and applications are designed on the atomic level and scanning tunneling microscopes allow accurate monitoring and assessing.

(Follow-up with a quiz, as described in the Assessment section.)

Lesson Background & Concepts for Teachers

Wave-particle duality

According to the wave-particle duality all particles also exhibit wave nature. The wavelength is inversely proportional to the particle's momentum:

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

However, for massive objects that wavelength is negligible. One way to confirm the wave nature of particles is interference. The interference pattern arises because of the wave nature. Usually interference is observed for light, but interference patterns have also been observed for macroscopic objects, e.g. buckyballs (spherical C₆₀ fullerene), using Young's double slit experiment.

Schrödinger Equation

The wave function of a quantum particle is the solution of the Schrödinger equation. The Schrödinger equation is a partial differential equation that is time dependent in its most general form. For simple cases, e.g. the harmonic oscillator, the solution/wavefunction can be calculated analytically. The square of the amplitude of the wave in a region is proportional to the probability of finding a particle in that region. Hence in quantum mechanics information about a particle takes the form of probabilities. This concept is closely related to the Heisenberg uncertainty principle, which says that it is impossible to know all information (like momentum, position) of a particle simultaneously (hence "uncertainty").

Quantum tunneling

Solving the Schrödinger equation for a potential barrier shows that the wavefunction is not zero behind the barrier and hence the particle has a nonzero probability to be found on the other side. The probability of tunneling depends on the width and height of the barrier. The wider or higher the barrier, the lower the probability of tunneling.

Scanning tunneling microscope

The scanning tunneling microscope was developed in 1981 and earned its inventors, Gerd Binnig and Heinrich Rohrer (at IBM Zürich), the Nobel Prize in Physics in 1986. It allows 0.1 nm lateral resolution and 0.01 nm depth resolution. The tip is usually made of tungsten/wolfram and is brought very close to the surface to be examined and a small voltage is applied. The gap is typically between 4-7 Å.

Electrons can tunnel through the gap resulting in a current, called *tunneling current*. While moving along the x-y-plane the current is measured as a function of the gap. The current depends on the material's surface, which is the local probability density of quantum mechanical states.

Scanning tunneling microscopy is challenging from the engineering point of view, as it requires extremely clean and stable surfaces, sharp tips, excellent vibration control, and sophisticated electronics.

Image Insert Image # or Figure # here [note position: left justified, centered or right justified]

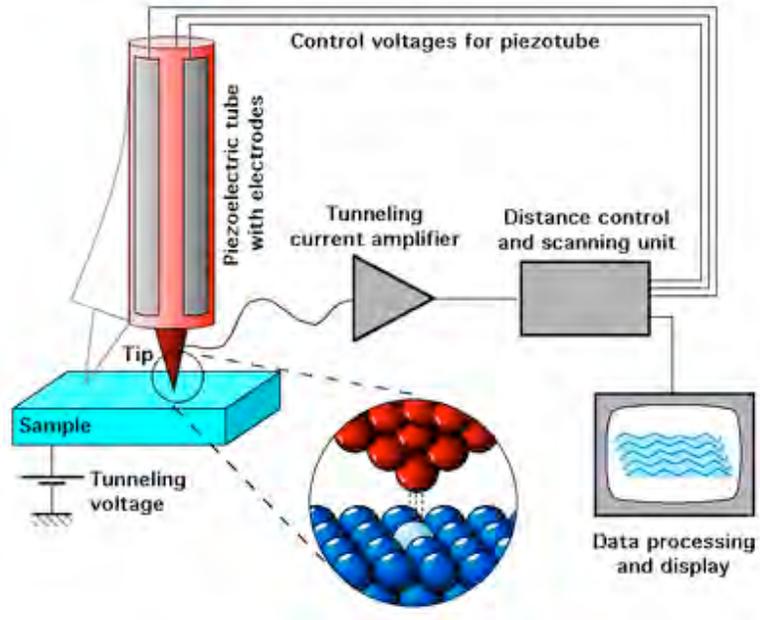


Figure #

ADA Description: Drawing of scanning tunneling microscope principles

Caption: The tip is brought very close to the surface of the material under study. Applying a small voltage allows electrons to tunnel from the tip to the sample thereby producing a small current. The current is a function of the distance and therefore allows to assess the surface.

Image file:

lesson_quantum_tunneling_fig_2_web_scanningtunnelingmicroscope.png

Source/Rights: Copyright © Wikipedia

http://upload.wikimedia.org/wikipedia/commons/thumb/f/f9/ScanningTunnelingMicroscope_schematic.png/400px-ScanningTunnelingMicroscope_schematic.png?

Vocabulary / Definitions

Word	Definition
quantum mechanics	Branch of physics on the (sub-)atomic scale.
tunneling	Quantum mechanical phenomenon where a particle tunnels through a barrier that it classically could not surmount.
scanning tunneling microscope	Instrument based on quantum tunneling for imaging surfaces on the atomic scale.

Associated Activities

Lesson Closure

So what do you think of the tennis ball now? (Throw tennis ball against the wall) Is it possible for it to tunnel through the wall? Technically yes, but the probability is so small that you will never experience it in the life of the universe. However, what if I would throw a “quantum tennis ball” against a “quantum wall”? Would there be a good chance for it to go through? (Take students responses)

Assessment

Pre-Lesson Assessment

Discussion Question: Ask a few questions to get students to think about the upcoming lesson and to assess prior knowledge. After soliciting answers, explain that these questions will be answered during the lesson.

- What do you know about quantum mechanics?
- How is the physics different on the quantum mechanical level?
- How can we assess or even see the atomic structure of materials?

Post-Lesson Assessment

Quiz: Ask a few questions to get students to think about the upcoming lesson and to assess prior knowledge. After soliciting answers, explain that these questions will be answered during the lesson.

Post-Introduction Assessment

Quiz: Have students complete the attached tunneling Quiz.

Lesson Extension Activities

None

Additional Multimedia Support

References

Attachments

Quiz.docx

Presentation.pptx

Presentation.pdf

Other

None

Redirect URL

None

Contributors

Lars Seemann, Mila Bersabal

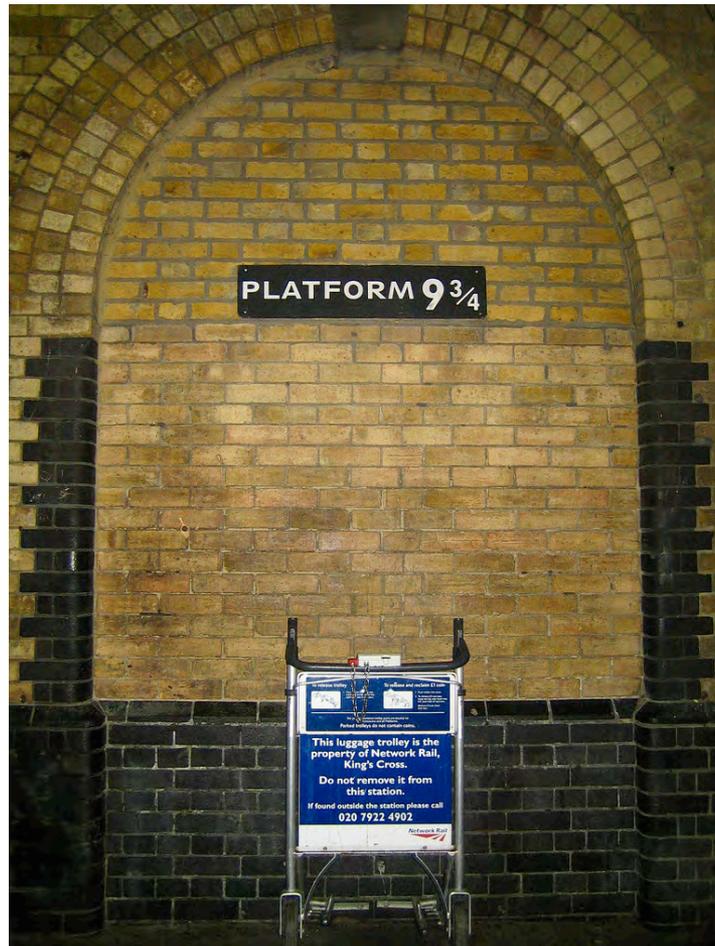
Copyright

Supporting Program

GK-12 Program at the University of Houston: Innovations in Nanotechnology and Nanosciences using a Knowledge, Applications, Research, and Technology (KART) Approach

Version: September 2010

Quantum Tunneling



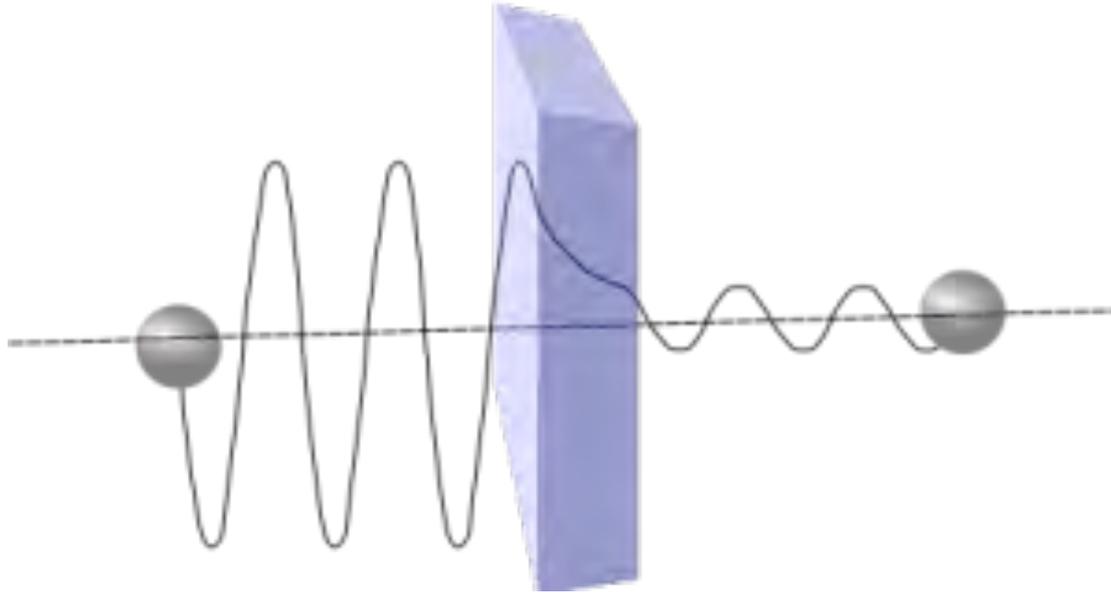
Wizards tunnel through a wall to get on the Hogwarts express

Recall:

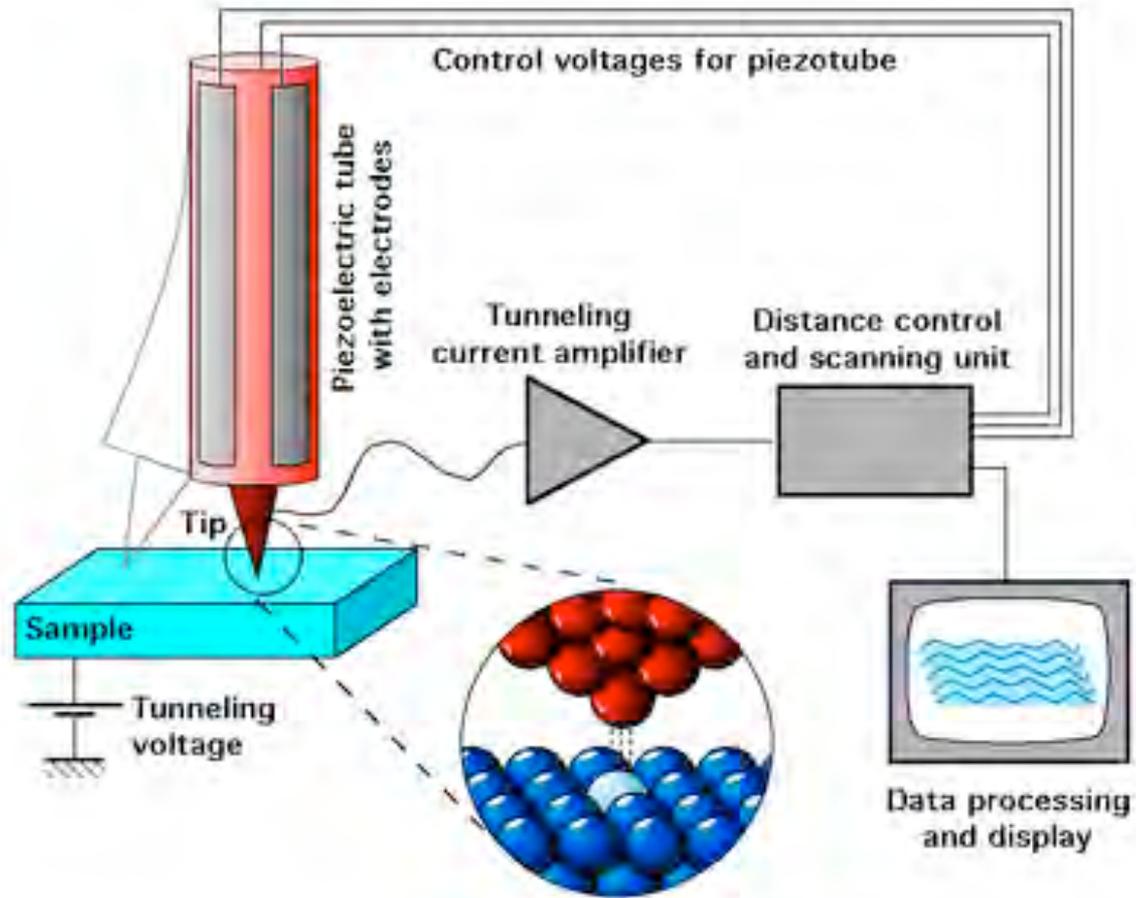
- Wave-particle duality:
All particles exhibit both wave AND particle properties
- De-Broglie wavelength:

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

Wave nature of particles allows tunneling:



Scanning tunneling microscope



In real life



Writing with atoms (or the lack thereof)

