1
Introduction

1.1
The Tunneling Process

There are many popular essays about time, history of the universe, teleportation or the possibility of time travel, but not much is reported about tunneling. However, the tunnel process is the basis of the origin of the universe, of the sunshine, and thus of life. It was discovered by Antoine Henri Becquerel (1852–1908), Figure 1.1, in 1886 while investigating the radioactive decay of atomic nuclei. This was then

Fig. 1.1 Physicist Antoine Henri Becquerel (1852–1908). He discovered the natural radioactivity. *© Bettmann/CORBIS*

Zero Time Space: How Quantum Tunneling Broke the Light Speed Barrier. G. Nimtz and A. Haibel

ISBN: 978-3-527-40735-4

Fig. 1.2 The couple Marie and Pierre Curie (1867–1934 and 1859–1906) in the laboratory. *© Bettmann/CORBIS*

examined more systematically by Marie and Pierre Curie (1867–1934 and 1859–1906), Figure 1.2. Marie Curie was a student of Becquerel's and she continued his research. Together with Becquerel the Curies received the Nobel prize in physics *"for developing and pioneering in the field of spontaneous radioactivity and the phenomena of radiation"*. The explanation of α-decay as quantum mechanic tunneling followed around 1928 by George Gamow (1904–1975) and simultaneously, but independently, by Edward U. Condon (1902–1974) and Ronald W. Gurney (1899–1953).

Incidentally, in 1927, Friedrich Hund (1896–1997) was the first to notice the possibility of the phenomenon of tunnel-

ing, which he called *barrier penetration*, in a calculation of the ground state in a double-well potential. The phenomenon arises, for example, in the inversion transition of the ammonia molecule, as presented in Section 5.1.1.

Our knowledge today of quantum cosmology tells us that the universe also came into existence through tunneling, the so-called 'Big Bang'. A stationary state of space and time of infinitely small dimension tunneled into our world and expanded until eventually today's state of our universe was reached.

The principle of tunneling can be shown with a simple picture: Particles like photons, electrons, nuclear particles, even atoms and molecules, can surmount mountains, even though they lack the energy to reach the peak. They reach the other side of the mountain by *tunneling* through it. This process, however, is not easy to understand, the *mountains* facing those particles, have no tubes, they are not made of material that through you could get easily. Rather they are impenetrable, insurmountable barriers, which physicists call *potential barriers*. In the same way as for man a massif is insurmountable, the attraction of the particles in an atomic nucleus seem like an insurmountable barrier. These forces hold the nuclear particles together as in a potential well. For light, which consists of an ensemble of single particles of light – so-called photons – the electronic shells of atoms, for example, form a barrier. These atoms are tough obstacles for quanta of radiation, like walls for tennis balls.

Even so, after some time, particles suddenly succeed in penetrating the apparently insurmountable potential

mountain. Figure 1.3 is supposed to illustrate this strange tunneling process. The thief would prefer to disappear with his loot through the wall.

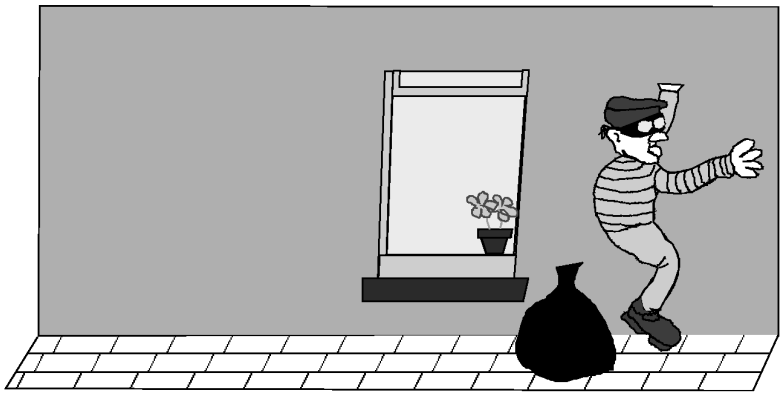

Fig. 1.3 Burglars would like the tunneling effect.

This is made possible by the tunneling process, for instance during the radioactive decay of atoms. Take uranium which, emitting α and β particles (helium nuclei and electrons), decays step by step into radium and eventually into lead. This was discovered by Marie Curie. Since the 20th century radioactive decay of isotopes with a short life time has been frequently used for diagnostic and therapeutic purposes in medicine. Radioactive decay of nuclei is the source of energy in atomic power stations.

Tunneling not only makes decay possible but also enables the build up of bigger atomic nuclei, the so-called nuclear fusion. Even in the center of the sun pressures and temperatures are not high enough to bring about nuclear fusion.

The hydrogen nuclei (also called protons) cannot manage to overcome the repulsive electric barriers. Helium nuclei can not, therefore, be built up. If, in spite of this, some hydrogen nuclei do manage to reach the valley and fuse then this is also caused by tunneling. Hydrogen nuclei fuse into helium nuclei and as a result release solar energy.[1]

The most fascinating aspect of the tunneling process is that the 'tunneling' particles not only penetrate potential barriers of any size, but at the same time also show an extraordinary time behavior. Both are part of the quantum mechanical nature of the tunneling process. In this, particles seem to travel with infinitely high speed through barrier spaces, which means in zero time and thus incomparably faster than light. Light travels fast, but at a speed which is still finite and measurable. In the tunnel, however, no time exists. In a figurative sense one could say, nothing happens in a tunnel, there is eternity. Contrary to existing ideas timelessness, which is eternity, is synonymous with the total absence of events, simply boring.

Tunneling in a way is as difficult to understand as Heisenberg's relation of uncertainty. It proves that you can either measure with high precision the location or the velocity of a particle, but not both at the same time. The tunneling

1) In the most terrible weapon known to mankind, the Hydrogen bomb, both processes, nuclear decay and nuclear fusion are used. First radioactive decay is ignited. Thereby electrically positively charged atomic particles, protons, are heated to millions of degrees Celsius. Through a fusion of protons another powerful burst of energy is set free. Such a hybrid bomb can release an energy equal to 60 million tons of the classical chemical TNT (trinitrotoluene).

process and the relation of uncertainty are quantum mechanical effects which force us to revise our ideas of space and time. Since the theory of quantum mechanics was introduced about a hundred years ago no contradiction of it has been found. Of course, this theory of ours will also not be able to describe the world for ever, but ever more frequently its validity is confirmed in all fields of physics. For instance quantum mechanics is frequently used in many applications in modern semiconductor technology or in optoelectronics. Generally, standardized measures for time and signal traveling time are being used in all technologies. Therefore tunneling with its unusual time behavior provokes not only fundamental questions in theoretical and applied physics, but also philosophical and theological questions concerning space and time.

1.2 Time, Space and Velocity

In the 5th century the philosopher Aurelius Augustinus (St. Augustine), Figure 1.4, wrote about 'time' in his *confessions*:

> *"What then is time? If nobody asks me, then I know, if I want to explain it, I don't know. Even so I maintain to know confidently, there wouldn't be a past time, if nothing had passed, no future time could be, if nothing came towards us and the present time could not be experienced, if nothing existed"*. [3]

Fig. 1.4 Philosopher and Theologian St.Augustine (354–430).
© Bettmann/CORBIS

This statement hits the point, time is difficult if not impossible to describe. In any case, time describes an *experience, an event*. To the classical physicist time is a *measurable experience*. (For one hour I suffered from a terrible toothache; I spent an exciting week diving in coral reefs.) Past, present and future are measurable and, for the traditional physicist, they are universally applicable, independent of place and movement.

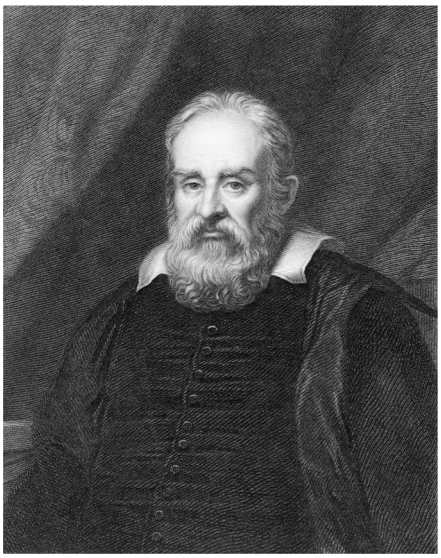

Fig. 1.5 Portrait of Galileo Galilei around 1600. *© Bettmann/CORBIS*

Around 1600 Galileo Galilei (1564–1642), Figure 1.5, watched the oscillation behavior of a chandelier which was hanging from the ceiling in Pisa cathedral, swinging in the draught, Figure 1.6. He was curious whether the time of swinging depended on the amplitude. He did not have a watch, so he used his heartbeat and the rhythm of certain melodies for time keeping. He discovered, that the swinging time of a pendulum depended on its length, not its weight. He claimed, swinging time was independent of amplitude, which is not exactly true, as we know today.

Isaac Newton (1643–1727), Figure 1.7, assumed around 1700, like many others right up to the end of the 19th century, that time was an absolute quantity. Today we know

Fig. 1.6 Galileo Galilei studied the pendulousness of a candelabrum at the cathedral of Pisa. Painting of Luigi Sabatellio, Florenz, Museo di Fisica e Storia Naturale. *© Archivo Iconografico, S.A./CORBIS*

that this is not the case. There is no objective time, no absolute time. The passing of time depends on the movements of the observer and of what is being observed. Time was degraded by Einstein's theory of relativity to a relative quantity. In quantum mechanics time is not even an observable, which means measurable, quantity.

Although the tunnel diode has been used as an electronic device since 1962, the time which a particle spends tunneling in the mountain was neither theoretically nor experi-

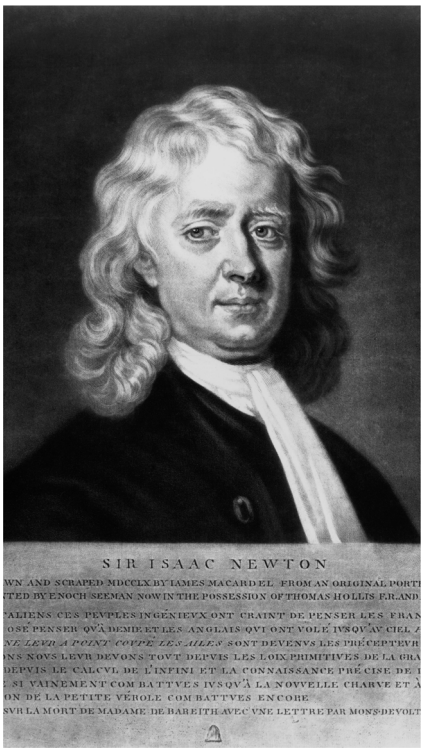

Fig. 1.7 Portrait of Sir Isaac Newton in the year of 1726. *©CORBIS*

mentally revealed. In this electronic device electrons tunnel through a mountain which, in semiconductors, separates the so-called valence band from the conduction band. The mountain is called a *forbidden band gap*. The consequence of this tunneling is that this material, when in contact with a certain voltage supply, abruptly becomes a strong electric conductor. It is like using a switch, one suddenly gets a high current. The time electrons spend tunneling barriers in this

often used device could not be defined until now. The cause of the problem measuring the tunneling time of electrons will be dealt with later.

Microwave signals (built up by light particles, so-called photons, which are quanta of electromagnetic waves, part of which are γ- and X-rays and light, as well as microwaves) were first measured by Achim Enders and Günter Nimtz in 1991/1992 at the University of Cologne [4]. These experiments in Cologne were provoked by an article in the journal *Applied Physics Letters* in 1991 [5]. In this, four Italian colleagues in Florence claimed that the speed of microwaves in the tunneling barrier measured by them was distinctly less than the speed of light in vacuum. Günter Nimtz, coauthor of this book, realized that these measurements could not be correct. He discussed this with Prof. Enders, at the time working with him in Cologne, who had developed a highly sensitive microwave apparatus, albeit for entirely different purposes. Enders got excited and pressed for an immediate repetition of the tunneling experiments. The following weekends were used to define the obscure tunneling speed. Initially, neither was aware of the fundamental question related to time behavior in the tunneling process. They were driven by sheer curiosity and ambition to reveal the secret of the tunneling time.

Contrary to their Italian colleagues, Enders and Nimtz observed an infinite signal velocity in the tunnel. According to their findings, the spread of the signal pulse was timeless in the barrier, it was instantaneous. The signal was spread across the entire tunneling barrier in zero time. It did not

need any time to get from the entrance to the exit of the tunneling barrier. In physics this is called *non-locality* in time, in theology omnipresent. A very short time delay happens, however, at the entrance of a barrier. This time effect will be discussed in detail in Section 5.1.2.

Seen from everyday life, this surprising result collides with many respectable publications with regard to *Einstein causality*, which postulates that nothing can move faster than the velocity of light. Which means that energies and signals cannot spread faster than the velocity of light. According to most books on the special theory of relativity a velocity beyond the velocity of light would allow a manipulation of the past, see for instance Refs. [2, 6].

Einstein causality, however, can only be applied mathematically correct, to the propagation of infinitely short signals [7]. This, however, cannot be applied to particles and signals which possess a natural time duration nor to the tunneling process, which can only be explained by quantum mechanics. Not even an infinite signal velocity can change the *primitive principle of causality: cause precedes effect*. The past cannot be changed by superluminal signal velocity. (Physicists distinguish between superluminal (faster than light) and subluminal (slower than light) propagation of waves). For science fiction this means there cannot be a time machine, no manipulation of the past. In Section 5.5 the principle of causality will be discussed extensively.

By the way, the Italian scientists, who had initiated the microwave experiments as a test for tunneling velocity, confirmed the correct Cologne results in the journal *Physical Review* [8].

Quite a few physicists *believe*, that a superluminal signal velocity is impossible and *cannot be accepted*. Their comments on this subject are rather emotional. Heated disputes can be found in professional and popular science media and of course on the internet. This discussion deserves attention, as measurement of superluminal digital signal transmission was demonstrated several years ago on a modern glass fiber line in a laboratory of the *Corning* company. We shall discuss this superluminal signal experiment in more detail in Section 5.3.2.

Professor Raymond Chiao at Berkley University supports the 'impossibility' of superluminal signal transmission. He is a pupil of the Nobel prize winner Townes, who took part in the discovery of the MASER–LASER. In many articles and discussions, Chiao points out that superluminal signal transmission is simply not permissible. Interestingly, however, members of his own laboratory at Berkeley have demonstrated that quanta of light have tunneled at superluminal speeds. Measurements with the same experimental set-up confirmed that group velocity and energy velocities are superluminal [9].

At the Lake Garda meeting *"Mysteries, Puzzles and Paradoxes"* in 1998 Prof. Rudolfo Bonifacio of the University of Milan ascertained:

> *"The detector clicks faster, when a photon has gone through a tunnel than when it has traveled at the speed of light. Therefore the photon which has gone through the tunnel was registered as superluminal."*

Recently physicists like Markus Büttiker and Sean Washburn contributed to this subject in *Nature* (March 20th, 2003), claiming signal velocity must be slower than the velocity of light in a vacuum [10]. This claim cannot be correct as all light velocities are equal in vacuum, whether the velocity of energy, signal, group or phase of electromagnetic waves. In the end the authors attenuated single photons in order to rescue the subluminal signal velocity in their theoretical model. However, a single quantum of light cannot be attenuated in the elastic tunneling process. These quanta can be reflected or tunneled, but exist only virtually in a barrier as they do not spend time in traversing the barrier. In compliance with their text, the authors wanted to reduce the energy of single photons, which are the smallest units of electromagnetic waves, and thereby reduce Planck's constant?

The problem's solution lies in three often overlooked properties of the tunneling process and of a signal. We are going to deal with this in detail in Chapter 5:

- The tunneling process is part of Quantum Mechanics and cannot be described by the special theory of relativity.
- Physical signals are frequency band limited as we are familiar with, for instance, acoustic high fidelity signals having a frequency band up to 20 kHz. If the frequency band limitation were not the case, signals would need infinite energy.

- Superluminal signal speed does not violate the primitive causality saying that cause and effect cannot be exchanged.

In 1962 a publication on the theory of quantum mechanics was presented by Thomas Hartman, who described all known superluminal phenomena of tunneling and exposed all subsequent theoretical efforts as wrong or superfluous. This was dealt with at length by Steve Collins and his colleague in the *"The quantum mechanical tunneling time problem – revisited"* [11] and also by Günter Nimtz and Astrid Haibel in *"Basics of Superluminal Signals"* [12].

Recently, several physicists, first in France then in the United States, even measured negative speeds of light pulses. The result was that the peak of a pulse arrived at the exit of a medium before it had reached the entrance. Consequently, the speed of the peak traveled in the opposite direction in this special medium. Again the principle of causality does not suffer any damage, as the envelope of the pulse becomes reshaped, which means the peak of the pulse does not happen before the beginning of the original signal. Apart from that, the original information cannot be recognized anymore.

In this context it is interesting that two famous physicists, Arnold Sommerfeld (1868–1951) and Léon Brillouin (1889–1969), had already in 1914 calculated a negative group velocity in a case similar to the one just mentioned. Brillouin, however, claims in his famous book *Wave Propagation and Group Velocity* that a negative group velocity has no physical meaning [13]. Many decades later modern sophisticated

electronic equipment made it possible to prove the possibility of an allegedly *non-physical* negative group velocity.

The counterpart of superluminal and negative velocities also got into the headlines recently: slowed down and stopped light. This phenomenon of slowing down light does not contradict Einstein's special relativity, but again is a quantum mechanical process which cannot be explained by the classical physics of Newton and Maxwell.

This book shows and explains the strange behavior of time and therewith velocity of tunneling. Our introductory chapters therefore deal with these fundamental physical concepts and quantities – time, space, and speed, extensively. Our understanding of these quantities has changed drastically during the last three centuries. Time is no longer regarded as absolute and signal and energy speeds are limited in their quantity by the speed of light in a vacuum. The tunnel process is something that cannot be explained by classical physics nor by the special theory of relativity, only by quantum mechanics and quantum electrodynamics.

After the introductory chapters we shall explain the spectacular qualities of tunneling. Our final sections deal with the problem of violating Einstein causality and also with superluminal phenomena, which follow speculatively from the general theory of relativity.