Topics from modern physics

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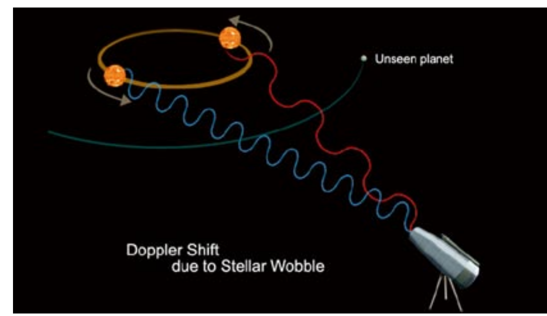
When I started my studies in physics, almost 40 years ago, I found the subject fascinating, although not as exciting as I do today. This may seem strange as instruments and methods have improved, theories have been refined, and many discoveries have been made over the past 40 years. Our understanding of the laws of nature has definitely increased, but new questions have also come up. Nature is, more than ever, both a difficult and a beautiful puzzle.

Physics is the science of nature at a fundamental level. It extends from particle physics, in which the smallest building blocks of matter are studied, to astrophysics, the study of the universe. Physicists are not only engaged in studying nature, but in the development of tools that lead to new science, solve societal challenges or provide a better daily life. The intention in this short summary is not to review the whole of physics, but to highlight some interesting aspects of modern physics.

Exoplaneter

Planets that orbit a star outside our solar system, were discovered in the 1990s, and have already become part of nature as we understand it. Over 3000 exoplanets have been discovered so far, and the number is increasing every year, with the development of observation techniques. Several techniques can be used to detect planets. The method used to detect the first exoplanets is based on measuring the variation in the radial velocity of a star caused by the Doppler shift of spectral lines. (figure below). Today, most observations are made with the help of satellites, using the so-called transit method, in which the periodical variation in the luminosity of a star, due to the passage of the planet in front of it, is measured. A surprising discovery is that there are large, heavy planets with very short periods of revolution, and thus high temperatures, in contrast to our own solar system.

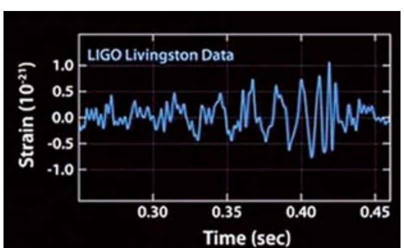


Observation of planets using the Doppler technique.

Planets have also been discovered in the so-called 'habitable' zone, where liquid water may be present, suggesting the possibility of life.

Black holes and gravitational waves

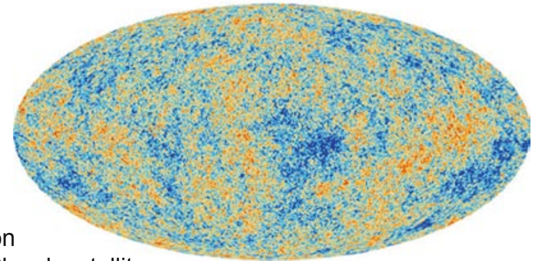
Black holes are massive, dense objects, whose gravitational field is so large that no radiation can escape from them. It is therefore impossible to see black holes directly, but the effects they have on their surroundings can be observed. Black holes can have masses ranging from several tens of solar masses to millions or even billions of solar masses. These gigantic black holes are expected to be found at the centre of galaxies. The enormous black hole at the centre of our own galaxy, in the Milky Way, has been predicted by studying the orbits of the stars closest to the centre of the galaxy, which are affected by the presence of this huge mass. New evidence for the existence of black holes came recently, in September 2015, with the detection of gravitational waves. The detector used for this is an impressive optical instrument called LIGO (the Laser Interferometer Gravitational-wave Observatory). LIGO consists of two large, very accurate, Michelson interferometers, separated by a distance of 3 000 km; one in Livingston, Louisiana, and the other in Hanford, Washington, USA. The variation in space-time caused by gravitational waves leads to a difference in the lengths of the arms of the interferometers, which can be measured with almost incredible accuracy. The gravitational signal, which lasted only a fraction of a second, is thought to be a consequence of the fusion of two black holes thousands of millions of light years away.



The detection of a gravitational wave.

Cosmology

The study of the history of the universe has developed tremendously during recent decennia thanks to accurate measurements of the cosmic background radiation in the microwave range (using, for example, the Planck satellite, measurements of the expansion of the universe (by studying supernovae, i.e. large exploding stars), and mapping of the distribution of galaxies in space. The history of the universe is described by a cosmological model that starts with the Big Bang, when the universe was very small, dense and hot. The model includes 68 % *dark energy* which causes the expansion of the universe to accelerate, 27 % *dark matter*, and less than 5 % *normal* matter. Several kinds of observations have provided and less than 5 % *normal* matter. Several kinds of observations have provided evidence for the existence of dark matter, but we do



Cosmic background radiation observed with the Planck satellite.

not yet know what it is. One hypothesis is that it consists of heavy, weakly interacting particles, which scientists are now searching for in several experiments, both here on earth and in space.

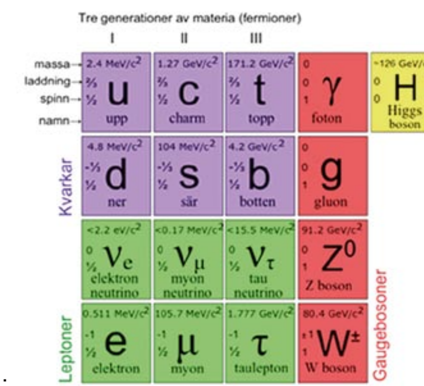
Particle physics

Within particle physics, the laws of nature and the basic building blocks of matter are studied. Experiments require high-energy collision processes to reach the resolution of the smallest subatomic particles. Large accelerators are therefore needed, such as the LHC (Large Hadron Collider) at CERN in Geneva, and experiments are performed by large research groups, sometimes consisting of several thousand scientists. The laws of nature and elementary particles are currently described theoretically using the Standard Model, which has been experimentally verified to high accuracy.

These basic building blocks and particles are called elementary particles, and include material particles such as quarks and leptons (examples of which are electrons and neutrinos), and particles that mediate the four fundamental forces in nature. Each of the material particles has a corresponding antiparticle. Hadrons, for example, neutrons and protons, are made up of quarks, while antiprotons, for example, are made up of antiquarks.

Three kinds of force-mediating elementary particles have been observed: Gluons (the strong force), photons (the electromagnetic force), and W and Z bosons (the weak force). The particle mediating the gravitational force, the graviton, has not yet been experimentally observed.

In 2012 the Higgs particle was detected in two experiments, ATLAS and CMS, at the LHC. This was a major triumph for particle physics as the BEH (Brout–Englert–Higgs) mechanism and the Higgs particle had been predicted almost half a century earlier to give mass to elementary particles, and could now be confirmed.



The Standard Model.

The most common elementary particles in the universe after photons are neutrinos. They are created by the weak force, for example, in stars, and interact extremely seldom with matter. For example, they can pass through the earth without being stopped. It was long thought that neutrinos had no mass. By measuring the neutrino flux in large detectors deep underground, scientists have been able to show that neutrinos can change character during their passage through the earth, for example, from muon to tau neutrinos. These so-called 'neutrino oscillations' mean that neutrinos have a mass. So far, we have only been able to determine the upper limit on this mass, but we know that the lower limit is not zero.

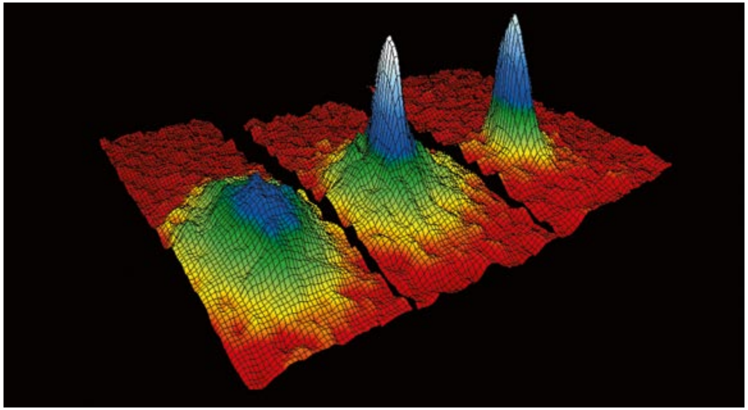
Particle physicists are now excited about new discoveries that will take us beyond the Standard Model. There are many competing theories, but experimental guidance is needed to show which one best reflects nature. We have to know what lies beyond the Standard Model to be able to explain, for example, what dark matter consists of, and why the universe consists mostly of matter, and not equal amounts of matter and antimatter.

New elements

One area of modern research in nuclear physics is concerned with creating and studying extreme nuclei, for example, those with a high ratio of neutrons to protons, or those that are non-spherical, for example, pear-shaped. Another interesting question is how many protons and neutrons a nucleus can have without spontaneously decaying. Very heavy, short-lived nuclei can be made through fusion, which can lead to the discovery of new elements. Recently discovered elements have been given the names nihonium (Nh, with atomic number Z=113), moscovium (Mc, Z=115), tennessine (Ts, Z= 117) and oganesson (Og, Z=118). These elements complete the seventh row of the periodic table, and the hunt for elements in the next row can start.

Cold atoms and condensates

Atoms and their interactions with, for example, light, are studied in atomic physics. So-called *cold* atoms are often used in experiments. These are achieved by cooling them to temperatures of micro- or even nanokelvin using various techniques often laser-based. In 1995, scientists were successful in cooling a gas of alkali atoms so that a Bose-Einstein condensate was formed. The figure on the right shows the condensation of rubidium atoms. These atoms are bosons, and if they have a sufficiently low energy and are sufficiently close together their wavefunctions will overlap, and the atoms will be in the same quantum mechanical ground state. Condensates have many interesting properties that can be used in various applications. The atoms in a condensate move coherently (i.e., together), just like photons in a laser beam. It is considerably more difficult to cool fermions to extremely low temperatures, and thus form a condensate, as fermions cannot be in the same state (according to the Pauli principle). Despite these difficulties,



Formation of a Bose-Einstein condensate.

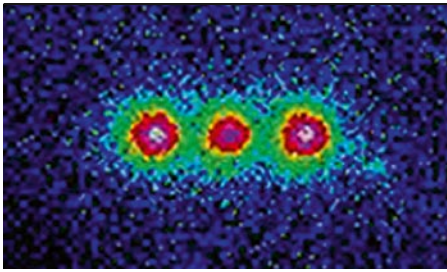
scientists have recently been able to condense fermions by forming *bosonic molecules* consisting of two *fermionic atoms*.

Quantum technology

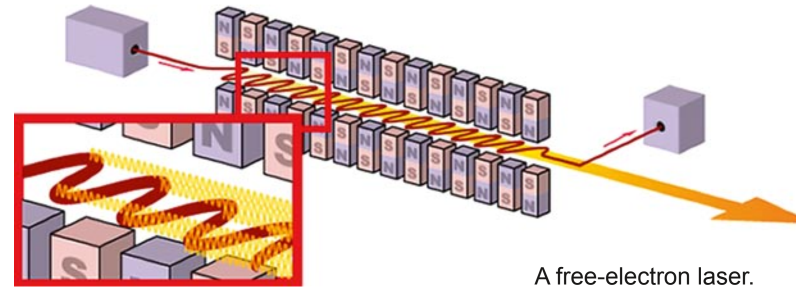
Our microcosmos is described by a theory developed almost a hundred years ago, quantum mechanics. Within quantum mechanics, matter behaves in a strange way: for example, a particle is not only a particle, it can also be a wave; its exact position and velocity cannot be determined simultaneously; and a particle can be in a superposition of different states. Particles are seldom isolated, and interact strongly with their environment. An ensemble of particles behaves differently from an isolated particle, and is often described using classical mechanics. The idea of an experiment using a single particle has long been an intellectual exercise. However, in recent years, methods have been developed for manipulating isolated ions in a trap, or a few photons in a cavity. These methods have many applications, from fundamental studies of the foundations of quantum mechanics, such as the transition from quantum mechanics to classical mechanics, to a new generation of atomic clocks using optical transitions in extremely stable, isolated ions.

Quantum mechanics also leads to intuitively bizarre predictions if one considers two (or more) particles in a so-called entangled state. When a measurement is made on one particle, it affects the properties measured in the other, even if they are a considerable distance apart. Experiments carried out at the end of the 20th century showed that these strong correlations could not be explained by a description based on a very intuitive local realism. Local realism assumes that an object exists, regardless of whether you are observing it or not (realism), and that it is only affected by its local environment (locality). Expressed more scientifically, the principle of local realism means that an object cannot be affected by another distant object at a speed faster than the speed of light, according to Einstein's theory of relativity.

As a result of basic research on the non-locality of nature, new ideas were conceived and developed where quantum mechanical properties were used in various applications. For example, information can be transmitted with complete security using quan-



Three Be ions.



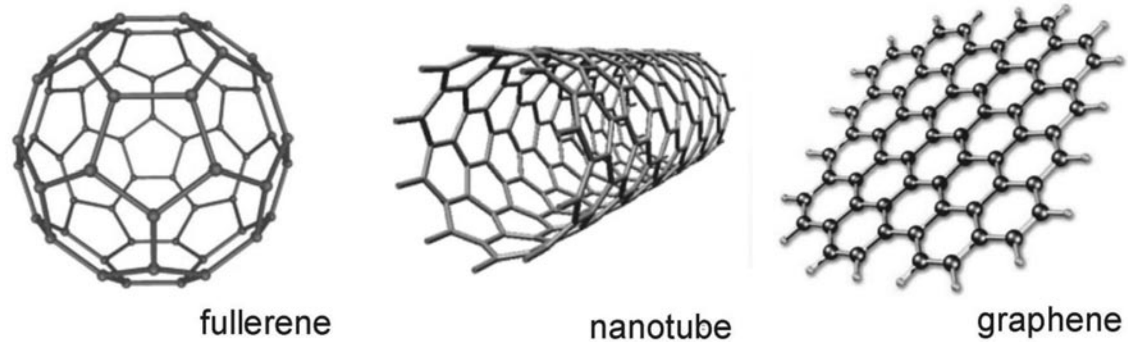
A free-electron laser.

tum cryptography, because if someone intercepts the message, both the sender and the receiver will be aware that the message has been intercepted. It is now possible to buy quantum cryptography equipment. Another application, which is still a vision of the future, is the quantum computer, which uses quantum bits (a superposition of two states, often called 0 and 1) instead of normal bits (0 and 1) for calculations. This application makes use of the natural parallelism in quantum mechanics, allowing simultaneous calculations with the superpositions of 0 and 1, and not first with 0 and then with 1. Several suggestions have been made regarding the physical components of a quantum computer, from trapped ions, to cold atoms and superconducting Josephson transitions. These components are already being used as *quantum simulators*.

Laser radiation

Our ability to control light has been improved considerably over recent decades. Lasers have revolutionized both science and everyday life. Laser research is being pursued in several directions: to increase the power, both the average power and peak power (which today is in the petawatt (1015 Watt) range), to extend the wavelength range, from the X-ray region to the infrared; to shorten the pulse length (down to a few femtoseconds) and, finally, to improve the coherence (which means that the beam propagates at exactly the same frequency, amplitude and phase over a long period of time). Conventional lasers make use of the transition between two levels in an atomic or molecular system. Energy is pumped into the system so as to cause a population inversion between the two levels. Today, laser light (or laser-like light), can also be created using new physical processes. In parametric processes, energy is never stored in the medium, but is converted from one kind of light to another. An example of this is high-harmonic generation in a gas, which leads to very short light pulses in the extreme ultraviolet region, with pulse lengths of only a few tens of attoseconds (1 as = 10^{-18} s). A free-electron laser makes use of relativistic electrons from a linear accelerator.

Radiation is produced by the oscillation of pulses of electrons in an undulator, which consists of a row of magnets with alternating poles (as shown in the figure). The radiation is coherently amplified as the pulses of electrons are modulated in a well-defined way by the light they generate. Free-electron lasers today can produce laser pulses with wavelengths in the X-ray region.



Carbon-based nanostructures.

Matter

As in the case of lasers, our knowledge concerning matter and our ability to control it have increased dramatically in recent decades. Older textbooks describe matter as being solid, liquid or gas. Today, this is far too simple a picture. Examples of other phases of matter are magnetic phases, superconductors, superfluids, plasmas, gels, polymers, etc. Within condensed matter physics, solid materials are classified as ordered (i.e., crystalline) or disordered (i.e., amorphous, such as glass). Band structure theory is used to categorize crystals as metals, insulators or semiconductors. But even this is too simple. A new area of research within the physics of condensed matter is concerned with creating materials that are good bulk insulators, but which are electrically conducting on their surface. Smart semiconductor structure designs have also opened up completely new research fields in low-dimensional systems.

Materials research leads to numerous applications. Semiconductors such as silicon (Si) and gallium arsenide (GaAs) form the basis of our increasingly powerful computers and mobile phones, and for fiberoptic communication, all of which have revolutionized our daily lives. Other applications include the development and production of materials suitable for efficient solar cells, which become increasingly more important for energy production, and materials for light emitting diodes, which can be used to produce light sources that are at least ten times more efficient than normal light bulbs.

Another successful development in solid state physics is nanotechnology. New techniques have made it possible to manipulate matter on the molecular scale, between 1 and 10 nanometres. Examples of nanomaterials with a single layer of atoms are carbon structures such as fullerenes, carbon nanotubes and graphene, a two-dimensional crystal (as shown in the figure). Other nanostructures, such as nanowires and quantum dots can also be produced from metals and semiconductors. There are many fields of application, for example, in medicine, photonics and electronics.

Nanostructures are usually investigated with electron microscopy, which has reached an almost unbelievable precision, making it possible to study nanomaterials on the atomic scale. Another method that has revolutionized materials science is scanning tunnelling microscopy, which is based on the concept of quantum tunnelling, strongly dependent on the distance to the surface. The surface structure of an electrically conducting material can be mapped on the atomic scale (~0.1 Å) by scanning an extremely narrow metal tip (of the order of a few atoms) over it. Atomic-force microscopy, which measures the atomic forces between the tip and the surface being studied, can also provide fine-detailed information on biological materials, which are not usually sufficiently conducting for scanning tunnelling microscopy.

A plasma is a material phase that contains free electrons and ions. Plasmas are found naturally in stars and interstellar space. They can also be created in the laboratory, and are used in fusion research, where scientists are attempting to bring about the fusion of tritium and deuterium (isotopes of hydrogen) to make helium and energy, using high-power lasers or high magnetic fields (tokamak). The aim is to produce more energy than has to be supplied to induce the fusion reaction in order to develop a fusion-based power plant.

On the borders of chemistry and biology

Apart from purely physics research, new areas are constantly being developed that involve, for example, chemistry or biology. One example of this is optical microscopy beyond the diffraction limit, which makes use of ingenious laser techniques combined with light-emitting chemical compounds, and is used in biology and medicine. Another example is the use of methods developed in statistical physics to predict the development of a virus population and for the study of neural networks.

Despite the enormous advances made in recent decades, or perhaps because of them, we are facing many new questions such as whether or not there is life outside our solar system. Gravitational waves provide us with a new way of regarding the universe: What will it look like? What is dark matter? Why does matter dominate over antimatter? Will physicists be able to describe gravitation (and find the predicted elementary particle, the graviton) together with the other forces of nature in a unified way? When will quantum computers or fusion power plants be realized, and what will they look like? What new inventions will help save lives on our planet?

Physics is more exciting than ever before!