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Einstein for schools and the general public

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Abstract
In April 2005 the World Year of Physics (the Einstein Year in UK and Ireland) was celebrated with an Einstein week in Stockholm House of Science. Seven experiments illustrated Einstein's remarkable work in 1905 on Brownian motion, the photoelectric effect and special relativity. Thirteen school classes with 260 pupils, 30 teachers and 25 members of the general public took part in the different activities. The experiments and the Einstein theme have become an appreciated part of the modern physics activities in House of Science. This shows that physics themes with a set of related experiments have a role to play in school education.

Introduction

Albert Einstein's theoretical achievements in 1905 and the remarkable development that followed were the basis for what is still known after 100 years as modern physics. The experiments that demonstrate Brownian motion, the photoelectric effect and the special relativity can all be done at school and made accessible also to the general public. In House of Science the Einstein experiment theme was offered to three target groups; teachers, school classes and the general public.

House of Science

House of Science in Stockholm is a science laboratory for physics, astronomy and biotechnology, entirely devoted to schools (Ref. 1). The aim is to make modern science accessible to teachers, school classes and individual students, and to make the students interested in today's natural science. House of Science is part of AlbaNova University Centre, which is a part of Stockholm University and the Royal Institute of Technology. During its first three years (2002-2004) more than 30 000 students and almost 1000 teachers visited the laboratories.

Einstein theme activities

During the week 18 – 22 April 2005 teachers were able to bring their classes to House of Science to acquaint themselves with Einstein's work in 1905 (Ref. 2) and related experiments. Teachers were also invited to a special evening during the week with a program covering talks and experimental activities. The general public could take part in a similar program the following evening. For all the target groups, the emphasis was on laboratory exercises complemented with demonstrations and presentations by researchers from AlbaNova University Centre. The experimental activities are all related to the miraculous year 1905 and

Einstein's theories: the Brownian motion (1 demonstration), the photoelectric effect (1 experiment), and special relativity (5 experiments or demonstrations).

Brownian motion

The Brownian motion is named after the botanist Robert Brown, who in 1827 was puzzled by the random jiggling motion of pollen grains in water. In 1863 it was suggested that this effect was due to the random bombardment of the water molecules, but it took until 1905 before the effect was properly and quantitatively described. One of Einstein's papers (Ref. 3) from 1905 dealt with the irregular motion of particles suspended in a solution. By applying results from the statistical theory of gases Einstein could provide the theoretical framework that made it possible to relate the jiggling movements of small, macroscopic objects to the existence of atoms and molecules and the determination of their size.

The Brownian motion was demonstrated to all categories of visitors in House of Science during the Einstein week (Fig. 1). Illuminated smoke particles were used to show their random motion caused by the interaction with air molecules. Smoke from a match was inserted into a small glass chamber illuminated by a 4mW green laser (Fig. 2). The chamber with the illuminated smoke was placed under a microscope and observed with a Video Flex camera. The resulting image was projected on a screen where bright smoke particles performed their random walk (Fig. 1). As the depth of field of the microscope is very small, the particles were constantly moving in and out of focus. This turned out to be an advantage as only a rather small number of smoke particles were in focus at the same time and it also emphasized that the movement occurred in all directions.

The Photoelectric effect

Einstein was awarded the Nobel Prize in Physics in 1921 for his work in theoretical physics (Ref. 4), especially "for his discovery of the law of the photoelectric effect". That light hitting a metal surface can knock out electrons, had earlier been studied by Philipp Lenard, who received the Nobel Prize in Physics for his work on cathode rays in 1905, the year that Albert Einstein explained the photoelectric effect. According to Einstein there is a relation between the frequency of the light and the velocity of the ejected electrons. This effect can be understood if light is described as a stream of particles, photons.

In order to explain the energy distribution of the radiation from a black body, Max Planck had in 1900 suggested that radiation consists of small packets of energy, quanta, and that the energy of the quantum is inversely proportional to the wavelength of the radiation, that is proportional to the frequency ($E = h\nu$, where h is Planck's constant).

The students were able to make an experiment on the photoelectric effect and to determine Planck's constant. A mercury lamp emitted light that passed a grating. The light was thereby split into different wavelengths which could in turn be directed so that they hit the metal surface. The students examined how the energy of the ejected electrons varied with intensity and energy of the light. By measuring the energy of the electrons for different energies of the light it was possible to determine Planck's constant by using Einstein's photoelectric law. At the same time they tested Einstein's idea that light consists of particles, photons. They also found that the intensity of the light did not influence the energy of the emitted electrons, which was expected according to the classical theory of Maxwell.

Special relativity

Cosmic muons and Einstein's time dilation

A continuous cloud chamber with 40 x 40 cm observational area (Fig. 3) was used to study the tracks from secondary cosmic radiation. Among the particles created in the upper atmosphere are muons with a mean life time of around 2 μs. Muon tracks are mostly seen as diffuse spots in the chamber. The muon flux is around $100/m^2 \cdot s$. According to classical physics it is surprising that so many muons created at high altitudes, typically above 20 km, can make it down to the Earth, as they would be expected to travel on average only around 600 meters before they disintegrate to electrons (or positrons) and neutrinos.

The explanation that they survive long enough to make it down to Earth and can be seen in the cloud chamber is of course Einstein's time dilation (Ref. 5). The muon lifetime is prolonged by a factor of perhaps 40 or more (as viewed from the cloud chamber frame) due to its high velocity and several of the muons thus have time enough to reach the cloud chamber.

From the muon perspective the situation looks different. In the muon's rest system the life time is around 2 μs, but Einstein's special relativity again solves the problem of reaching the Earth: the depth of the atmosphere is shortened by a factor 40 because of the length contraction and therefore the muons experience an approximately 500 meter deep atmosphere rushing towards them, a distance which most of them can travel during their lifetime.

Positron-electron annihilation

When Paul Dirac in the late 1920s worked on his relativistic theory for electrons he hit upon the problem with negative energy solutions. He was in fact solving Einstein's equation $E^2 = (pc)^2 + (mc^2)^2$ for the total energy E of a free electron. The negative solution was interpreted as representing a new type of matter: antiparticles, with different sign of the electric charge than the particle. Dirac published his results in 1931 where he suggested a new particle: the positively charged anti-electron (later named positron). Already the next year Paul Anderson discovered tracks in a Wilson cloud chamber that had been created by a positively charged particle with about the same mass as the electron. It turned out to be Dirac's anti-electron.

In the 1970s the technology of computed tomography (CT) had been invented and was being applied to medical imaging. The γ-radiation emitted when electrons and positrons annihilate could be used for this purpose. In most of the annihilations two photons are simultaneously emitted back to back (to preserve linear momentum), each with an energy of 511 keV corresponding to the rest mass energy of the particles. These can be registered by detectors coupled in coincidence to eliminate background radiation. The positron source should be situated somewhere on the line joining the two detectors that have detected the pair of photons. By detecting several such coincidences from different pairs of detectors the precise location of the source can be pinpointed. This is the idea of the PET camera (Positron Emission Tomography). House of Science has a small PET camera with two pairs of detectors, each pair coupled in coincidence with a time window of 40 ns (Fig. 4).

Speed of light

In his special relativity (Ref. 5) Einstein postulated that the speed of light in vacuum is constant for all observers. It is one of the fundamental constants in modern physics. In two different experiments the students were able to directly measure the speed of light. The most straightforward way was to measure the time it took for a light pulse to cover a certain distance. The House of Science has two experimental sets in which a light pulse is emitted and reflected in a mirror back to a detector. Using a fast oscilloscope it was possible to measure the time it took between emitting and receiving the pulse. The distance the light pulse covered was measured with a tape measure, and the speed of light was calculated. Another way to determine the speed of light was to measure the difference in phase between emitted and received light. The intensity of the emitted light was modulated with a frequency of 50 MHz. The light was reflected back by two mirrors. Using an oscilloscope the difference in phase between the emitted and received light was measured. The mirrors were then displaced so that the distance the light covers changed the phase by half a period which corresponded to half a wavelength of the modulating frequency. Knowing the frequency and the wavelength the speed of light could then be calculated.

Relativistic electrons
Einstein's theory of special relativity stated that nothing can move faster than light. When the speed of a particle is approaching the speed of light relativistic effects have to be included in the calculations. The task for the students was to determine the speed of the electrons emitted by the radioactive substance ^{90}Sr. By letting a beam of electrons pass through a magnetic field and measuring the deflection angle it was possible to determine their velocity, the higher the speed the smaller the deflection (Fig. 5). The speed of the electrons was first calculated using classical physics where the students found that they moved with a velocity of about 530 000 km/s for a deflection angle of 40 degrees, much faster than the speed of light. If they instead used Einstein's relativistic mechanics (Ref. 5) in their calculations they arrived at the more likely speed of about 260 000 km/s.

Solar spectrum
The work of Einstein has helped explain how the Sun generates its energy through fusion of hydrogen into helium. His famous equation $E=mc^2$ (Ref. 6) saying that mass and energy is equivalent, explains how the Sun is able to generate its large amounts of energy. The fusion process taking place in the centre of the Sun can be summarized by the relation:
$4\ {}^{1}H \rightarrow {}^{4}He + 2\ \nu_e + 2\ e^+$ + energy. Four hydrogen nuclei are about 0.7% heavier than one helium nucleus. This lost mass is turned into the energy powering the Sun. Each second about 600 million tonnes of hydrogen is fused into helium which results in the conversion of 4 million tonnes of matter into energy, most of it in the form of gamma-rays. These gamma-rays are trapped in the Sun for hundreds of thousands of years. On their way to the surface the photons are constantly being absorbed and reemitted, and the energy of each photon is gradually decreasing until it finally emerge at the solar surface as visible light.
In spite of this large burning rate, the supply of hydrogen is sufficient to power the Sun for another 5 billion years.
In this experiment the students studied the solar spectrum using a CCD spectrometer. From the measured spectrum, a blackbody spectrum containing numerous absorption lines, the students were able to determine the temperature of the Sun, and also identify different elements in the solar atmosphere and molecules in the Earth's atmosphere (Fig. 6). From the blackbody curve they were able to accurately determine the temperature of the solar surface to about 5800 K. The observed absorption lines showed the presence of hydrogen, as well as iron, calcium and magnesium in the solar atmosphere.

The laboratory visits
Teachers
One evening during the Einstein week was devoted to school teachers. The evening began with demonstrations and experiments. Two researchers from AlbaNova University Centre gave talks about Einstein related topics. One of the talks explained the special relativity in a comprehensible way using exclusively space-time diagrams, while the other talk presented recent advances in astronomy about dark matter and energy. The evening ended with a discussion of the best way to disseminate physics to pupils of different ages.
This evening provided the teachers with tools and ideas how to illustrate and explain different aspects of modern physics and relativity, which has often been asked for by the teachers. We have noticed an increased interest in the Einstein related experiments from the teachers after this week.

Pupils
Schools in the Stockholm region were invited to book activities in our laboratories during the Einstein week. The week was soon fully booked. A group usually spent 2-3 hours in the laboratories. A class was divided into 2 or 3 groups with 10-15 pupils in each. While one group was doing laboratory experiments the other was looking at demonstrations, and after half –time the groups switched activities. Some of the classes could also listen to talks by researchers from AlbaNova. The name Einstein still arouses the curiosity of young people and that doing experiments directly connected to him is a good way to increase interest in physics. The pupils were fascinated by the ease by which they were able to measure the speed of light. They also could spend a long time watching the cosmic muons and other particles in the cloud chamber, which brought up many questions and speculations. Another activity that captured the pupils' interest and gave rise to discussions was the demonstration of Brownian motion.

General public
The evening for the general public started with demonstrations of Brownian motion and cosmic muons in the Wilson cloud chamber, followed by a talk on what Einstein did in 1905. Einstein himself took part in the form of short film sequences and a sound recording where he briefly explains the $E = mc^2$ formula.

After the talk the guests were invited to try some of the crucial experiments connected to Einstein's work. The size of the laboratory limited the number of participants to 25. The program where the general public can do modern experiments in physics complemented with lectures was very appreciated, and we hope to be able to expand these activities in the future. Often at such events for the general public we see that parents bring their children and together enjoy the excitement of physics. The support of parents and other adults outside of school is also important to arouse the interest in the natural sciences for children.

Summary
The Einstein theme includes a fascinating set of experiments that describe some fundamental concepts in modern physics. It illustrates that physics has an interesting history with many great personalities. The Einstein theme with laboratory experiments, complemented with observations of relativistic cosmic radiation and the mass powered radiation from the Sun, is now an integrated and appreciated part of the physics laboratory of the House of Science and demonstrates an interesting way to introduce both modern physics and the history of physics at school.

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Figure captions

Fig. 1 The Brownian motion of smoke particles are made visible on a screen with a microscope and a video camera.

Fig. 2 Detail of the Brownian motion experiment: The laser beam from a small 4 mW diode laser goes through the smoke-filled chamber. The light scattered from the smoke particles is detected with a microscope and a video camera.

Fig. 3 High school students studying cosmic muons in a Wilson cloud chamber.

Fig. 4 A simple PET camera. Each pair of movable detectors is coupled in coincidence. Coincidences, marked by sound and blinking LEDs, indicate that the source is situated at the crossing of the lines connecting the two detectors. During the demonstrations the source is covered.

Fig. 5 Finding the direction of the Lorentz force for relativistic electrons in a magnetic field .

Fig. 6 Solar spectrum registered by a CCD spectrometer. The peak of the Planck curve at 500 nm gives a surface temperature of 5 800 K. The strong absorption lines at 720 nm and 760 nm emanate from H_2O and O_2 in the Earth atmosphere. At about 660, 490 and 430 nm the first three lines of the solar hydrogen Balmer series are seen.