A Companion to Physics of the XXth century. Part 1.

Slide 2 presents a way to classify physical research in two directions: „inward" and „outward". This scheme had been proposed many years ago by Victor Weisskopf. He pointed out that on the one hand the physicists try to investigate the structure of matter at different levels, from atoms to quarks and beyond, and on the other hand - try to make use of the knowledge already acquired at a given level to look for different applications.

Thus, at the beginning of the XXth century the research was concentrated at the atomic level. Once the structure and interactions of atoms had been recognized the physicists turned to study nuclear physics („inward" direction) and began to apply knowledge of atomic physics to chemistry and condensed matter („outward" direction). The next step which took place in the second half of the XXth century allowed to study particle physics, while both atomic nad nuclear physics led to important applicatons, such as e.g. transistors or nuclear reactors, not to mention deeper understanding of astrophysical phenomena. In the first decades of the XXIth century we have the physics of quarks and leptons („inward"), and a lot of valuable applications from atomic, nuclear and particle physics (shown in the graph). We may only guess what new phenomena will be uncovered in the future (Slide 3).

The early atomic models (Slides 5-9) had to take into account the conclusions from numerous experiments. The models proposed by Jean Perrin, Lord Kelvin nad Philipp Lenard were only loose and qualitative suggestions. The model by Japanese physicist Hantaro Nagaoka (Slides 8-9) was constructed to explain also the phenomena of radioactivity, however more detailed calculations soon showed its instability. The model by Joseph John Thomson was an elaboration of Kelvin's suggestion and involved detailed calculations of certain properties of atoms (see Slides 16-19) to ensure relatively long life-time of atoms. By assuming that the electrons in an atom form a rotating ring Thomson had proved that radiation of energy from accelerated charges as required by classical electrodynamics, may be reduced by a huge factor (Slide 19).

Meanwhile American physicist Robert Millikan managed to determine the elementary charge with considerable precision (Slide 10). Notable progress occurred in the study of X rays (Slide 11). Slide 12 contains the list of important events in early atomic physics - to be discussed in the following Slides.

The first attempt to include quantum concepts into the model of the hydrogen atom was due to Arthur Haas from Austria. His calculation is explained in Slide 13. The numerical agreement of his final equation for the Planck's constant *h* was just a coincidence. His model was called a „carnival joke" because the paper was published during the carnival period in 1910. In England John Nicholson also tried to combine atomic and quantum concepts. He was the first to use the word atomic „nucleus" and also for the first time considered the angular momentum of the electron ring in his model. Unfortunately he also invented four „primary" atoms and maintained that all known chemical atoms are composed of these hypothetical units (Slides 14-15). It reduced his credibility.

The scheme of Geiger's apparatus to observe α particles is shown in Slide 21 (left illustration). The α particles entering from A and collimated by the slit D, passed through the thin foil E and hit the phosphorescent screen S - the hits could be observed as tiny flashes of light, so called scintillations. Geiger found that the width of the area on screen S in which the hits were seen depended on the number of foils placed at E (Slide 21, right illustration). It gave the proof that the α particles undergo scattering during their passage through matter. Rutherford became interested in this subject and asked Geiger and Marsden to investigate it in detail (Slides 23-25). Alpha particles were collimated by the pipe AB and could be observed on the phosphorescent screen S only if they scattered from the wall RR (Slide 24). The results were quite unexpected. It turned out that one in about 8000 incident α particles was reflected at a very large angle (Slides 25-26). Such backward scattering was extremely improbable in the Thomson's „plum-pudding" model of many small charges distributed within the atom, but provided evidence of the existence of the large central charge (Slide 27). In 1911 Rutherford published famous paper in which he derived formulas for the scattering of α and β particles by matter. He assumed the existence of a large electric charge in the centre of an atom. Originally he was undecided on whether the charge of that nucleus wass positive or negative, and only later he decided that the existence of a positively charged nucleus agreed better with experimental data (Slides 28-31).

Two years later Geiger and Marsden published the results of their extensive study of scattering of α particles and confirmed Rutherford's calculations (Slides 32-33). Rutherford's theory explained the scattering of α particles and hardly anything else, therefore it did not arouse much interest as summarized in Slide 36. In particular, it did not initiate discussion during the first two Solvay conferences (1911, 1913), which gathered the selected group of the most famous scientists of that time (Slides 34 and 35).

For many years the physicists tried to understand atomic spectra. Thousands of spectral lines have been measured and there have been many efforts to find some systematics in that huge amount of data. Johann Balmer who was the teacher of mathematics in the secondary school in Basel and amused himself with numerology, found a connection between the four lines in the spectrum of hydrogen. It was a purely numerical relation found by trial and error (Slides 37-38). Some physicists believed that spectral lines were manifestation of the harmonic vibrations within atoms. For this reason the tables of the reciprocal of the wavelength $1/\lambda$, called wavenumber, were prepared and studied (Slide 39). An important step was taken by Walter Ritz, who discovered that the wavenumber of every spectral line can be expressed as the difference of two spectral terms (Slide 40).

The breakthrough occurred in 1913 when young Danish physicist Niels Bohr published the paper *On the constitution of atoms and molecules*. He assumed that there exist in each atom a number of allowed orbits in which the electrons do not radiate (as required by classical electrodynamics) but move without any loss of energy. The spectral lines were interpreted as radiation emitted in transitions of electrons between allowed orbits. Bohr made use of the earlier ideas of Ritz, Nicholson and Balmer, and derived expressions for the wavelength of the observed

hydrogen spectrum (the Balmer series); he also predicted the existence of other spectral series in the spectrum of hydrogen which were soon discovered (Slides 42-43). The electrons orbiting the nucleus resembled the planets orbiting the Sun, hence the name: Bohr's planetary model. In spite of his success Bohr met with devastating criticism of his work, especially because of his abandonment of classical electrodynamics (Slides 44-45).

At that time the understanding of the periodic system of elements was poor. There was no known relation between the number of electrons in an atom and its position in the periodic system. The number of chemical elements was not established, and at times every radioactive substance was taken to be an element. Thus for example, uranium was designed to be element number 96 or even 118 (Slides 46-49). In 1913 Dutch lawyer Antonius van den Broek, who was interested in physics, proposed a solution which proved to be correct (Slides 50-52). He had to assume that there are electrons also in the atomic nucleus (Slide 53). The electron-proton model of the nucleus had been used for the next 20 years, until the discovery of the neutron.

Young English experimenter Henry Moseley made a systematic study of X ray spectra. He carried out precise measurements of the wavelengths of K_α -lines of 21 elements. Inspired by van den Broek he found a beautiful regularity in that the wavenumber $\nu(Z)$ of K_α for element Z changed in a regular way when passing from one element to the next, and using the chemical order of elements in the periodic system. The same regularity was found for the L_α lines. Moseley's results confirmed that the atomic charge Z corresponds to the atomic number of the element (Slides 54-57).

Meanwhile in Germany James Franck and Gustav Hertz (the nephew of Heinrich Hertz) performed famous experiment in which they intended to measure the ionization potential of mercury vapour molecules. Their results seemed at first to contradict Bohr's idea but they soon corrected their conclusions (Slides 58-60).

Arnold Sommerfeld extended the Bohr's model by adding two new degrees of freedom - elliptical orbits and quantization of orbits in space; it introduced two new quantum numbers (Slide 61). Polish theoretician Wojciech Rubinowicz discovered selection rules for transitions of electrons between allowed orbits (Slide 62). German physicists Stern and Gerlach confirmed the existence of spatial quantization (Slide 63). The progress in understanding the atomic structure was discussed in the subsequent Solvay conferences which have been resumed after the end of World War I (Slides 64-65).

In 1923 American physicist Arthur Compton unexpectedly discovered that X rays scattered on electrons as if they were not waves but separate quantities of energy (energy quanta) - Slides 66-68. Compton's result was a direct confirmation of Einstein's idea put forward in 1905.

Meanwhile the Bohr model experienced deep crisis. After the brilliant explanation of the hydrogen atom and its spectrum it could not serve any further towards the description of heavier elements. Bohr and his collaborators were ready to abandon the hypothesis of light quanta and even to sacrifice the conservation of energy and momentum at the atomic level (Slides 69-70); that idea was, however, at once contradicted by experiments.

In 1923 Louis de Broglie put forward the revolutionary hypothesis that particles such as electrons or protons should exhibit wave properties. It was soon confirmed experimentally by Davidson and Germer in the USA, and independently by George Thomson - the son of J. J. Thomson - in England (Slides 73-75). Young Dutch physicists Goudsmit and Uhlenbeck suggested that the electron may have yet another degree of freedom - its own angular momentum (similarly to the spinning top). This idea was initially ridiculed but soon found to be correct (Slide 72). The American physical chemist Gilbert Lewis proposed the name „photon" for the quantum of light (Slide 76).

The contributions of Compton, de Broglie, and Goudsmit and Uhlenbeck were important milestones in the development of quantum mechanics. The summary of important dates and the portraits of the founders of quantum mechanics are given in Slides 77-78.

Young German physicist Werner Heisenberg was the first to notice the source of failure of the old quantum theory. Its practitioners used classical concepts such as circular or elliptical orbits of the electrons as well as their positions, although these quantities were unobservable. In July 1925 Heisenberg published his famous paper in which he originated quantum mechanics dealing only with relations between observable quantities: energy of atomic transition, intensity of spectral lines etc. (Slides 79-81). Unfortunately he made use of matrix calculus which at that time was practically unknown to most physicists. Heisenberg's paper as well as the next one published in November together with Max Born and Pascual Jordan were treated with reservation.

In January 1926 Austrian physicist Erwin Schrödinger initiated wave mechanics, easily understood by all physicists. He devised the famous differential wave equation („Schrödinger equation") which became the basic tool for theoreticians to solve atomic problems. In Schrödinger's treatment the quantum numbers appeared as the solutions of the equation, whereas in the Bohr-Sommerfeld model they had to be assumed (Slides 82-83). No wonder that the physicists at once accepted the new approach, to the disappointment of Heisenberg, who attacked Schrödinger's result in harsh words. Schrödinger responded with similar aversion (Slide 84). Fortunately, a few months later Schrödinger found the proof of a formal identity of wave mechanics and matrix mechanics. Yet another form of quantum mechanics was developed by Paul Dirac in Cambridge (Slides 86-88). In 1927 Heisenberg discovered the fundamental uncertainty principle which defined the limit on simultaneous observation the position and momentum of particles (Slide 85 and additional explanatory Slides 96-114).

Initially Schrödinger interpreted the Ψ-wave in his equation as a measure of the electrical density at every point of the atom. This proved to be not correct. Max Born proposed the explanation that Ψ^2 at any place gave the probability of finding the entire electron there.

The Solvay conference in 1927 (Slide 89) again gathered the top world physicists, including the „youngsters" (Heisenberg, Pauli, Dirac) who played crucial role in building quantum mechanics. It was presented there as a complete and final theory od atomic phenomena, together with the „Copenhagen interpretation"

Paul Dirac developed the quantum theory of the electron (Slide 90). His fundamental equation allowed also existence of states with the negative energy values for an electron. Dirac initially thought that these states could correspond to positively charged protons. It was however proven that such a hypothetical particle necessarily had to have the same mass as the electron. This prediction of Dirac was confirmed experimentally in 1932 when Carl Anderson discovered the antielectron, now called positron (Slides 91-93).

Dirac, Born and others expressed the view that quantum mechanics provided the ultimate explanation for most of physics and the whole of chemistry (Slide 94). They were, however, surprised by many fundamental discoveries made after 1930 (see **Physics of the XXth century. Part 2**).

Additional explanatory slides are for those who may not remember physics from the school. When the beam of light falls on a screen with a small opening, the light undergoes diffraction (Slide 96). The shape of the diffraction pattern depends on the shape and size of the opening (Slide 97). The angular width θ of the central maximum of the diffraction pattern depends on the wavelength of light λ and the size of the opening in the screen Δy , from which one easily obtains „the uncertainty principle" $\Delta y \, \Delta p_y \geq h$, where h is the Planck constant: the position of the light photon cannot be determined better than the width of the opening Δy; making the opening narrower results in broadening of the central diffraction maximum, i.e. the increase of the uncertainty of the momentum component Δp_y perpendicular to the original direction x of the photon (Slides 98-99).

Similar analysis may be applied in case of passing of light through two openings (Slide 100) which results in the interference and diffraction pattern (Slides 101-102), in which the uncertainty principle make it impossible to determine from which slit came a given photon. Similar experiment had been performed with the two lasers (Slide 103). Diffraction occurs also for electrons and other elementary particles (Slide 105). Slides 106-111 illustrate the build-up of the diffraction pattern in case of a beam of very small intensity, so that the electrons reach the screen one by one. Finally, Slides 112-114 explain the physical reason for the interference.

Quantum mechanics provides us with a detailed quantitative description of atomic phenomena which are impossible to understand in the same way as we understand phenomena in classical physics. Thus the new meaning of the word „understand" involves calculations which give us a complete description of the behaviour of the electron and other particles (Slides 115-116).