A Companion to Physics in the XXth century. Part 2.

In Slide 2 we find the list of important discoveries and events in the development of nuclear physics. These events are discussed in the following Slides. Please notice the concentration of events in the year 1932.

By the year 1902 the number of identified radioactive substances was large enough to reveal that they form three radioactive series (Slide 3). Rutherford and Soddy proposed the theory of radioactive transmutations which was based on that idea. The number of identified and studied radioactive substances grew quickly, and the fourth series was discovered (Slides 4-5). In 1913 Frederick Soddy put forward the idea of isotopes (Greek: *topos* - place, *isos* - equal), different forms of the same element having different masses but the same atomic number, and occupying the same place in the periodic system (Slide 6).

Charles Wilson invented the cloud chamber (called also Wilson's chamber) which greatly improved detection of particles by showing their tracks. The first chamber was small (ca. 10 cm) but soon bigger chambers were built (Slide 7).

At that time it was believed that the hydrogen nucleus is the positive electron with the radius of about 1/1830 of the negative electron found in the cathode rays. That idea had been used in the first nuclear models, such as e.g. the model proposed by William Harkins (Slide 9) which presented the alpha particle (the helium nucleus) in the form of a flat „hamburger" of four negative and two positive electrons. The model proposed by Stewart had circular and elliptical orbits of electrons in the nucleus (Slide 10). In the „onion-like" model proposed by Gehrcke the nuclei of heavier elements were built from lighter nuclei (Slide 11). There existed also extremely complicated models such as the one shown in Slide 12. It had been jokingly compared to a Gothic cathedral. The number of other proposed nuclear models was large - see examples in Slide 26.

In England Francis Aston invented a way to measure exactly the masses of isotopes. His mass spectrometer and the results are shown in Slides 13-17. The particles having different masses underwent slightly different deflection in the magnetic field and hit the photographic plate (*F*-*G* in the upper illustration, Slide 13) in different places. Because of that the results of Aston's measurements resembled the photographs of atomic optical spectra (Slide 15).

During the Ist World War Rutherford worked on various projects connected with the war effort. In 1919 he could return to the study of radioactivity. He observed the first nuclear reaction when alpha particles emitted by the source D collided with the nuclei of nitrogen 14 and produced oxygen 17 plus hydrogen ($^{14}N + {}^{4}He \longrightarrow {}^{17}O + {}^{1}H$). The light hydrogen nucleus could be detected on the screen S even when the source D was put at a large distance from S (Slide 18). However at that time Rutherford proposed different explanations which included a hypothetical nucleus X of mass 3 (Slides 19-22). The correct identification of that reaction was established after the systematic study performed by Patrick Blackett (Slide 23), but even then stubborn Rutherford did not give up and tried to invent other explanations (Slides 24-25).

Meanwhile the physicists became aware of the „nitrogen catastrophe" explained in Slides 27-28. Another unexplained fact was that the two-body alpha-decay produced monoenergetic α particles while the beta-decay, also considered to be a two body process, gave electrons which had a continuous spectrum of energy (Slides 29-30).

Slide 31 lists important events which happened in the period 1930-1932, especially in the „wonder year" 1932. In December 1930 Wolfgang Pauli proposed the idea of a new particle, neutral and very weakly interacting with matter, which carried out certain energy in the beta decay, so that the decay energy was distributed among three, not two particles; for this hypothetical particle Pauli proposed the name „neutron" (it was later changed by Fermi into „neutrino", Italian for the small neutron). The experimental detection of neutrino was extremely difficult and was achieved only in 1956 (see Slides 80-82).

In 1930 Walther Bothe and his student Herbert Becker discovered mysterious, very penetrating radiation which was produced by exposing beryllium to alpha particles from radium decay (Slide 34). Two years later James Chadwick solved the mystery by performing series of experiments with different targets exposed to the radiation. He showed that the Bothe-Becker radiation is not electromagnetic in nature but consists of new neutral particles, the neutrons (Slide 35). Possible existence of such a particle was discussed earlier (Slide 36) but Chadwick's discovery took the physicists by surprise (Slides 37-38). Nevertheless, the neutrons helped rejecting the electron-proton model of nuclei.

In the same year Carl Anderson was studying cosmic rays and discovered the positively charged electron, the positron, postulated earlier by Dirac (Slide 39). Nevertheless the discovery had not been a consequence of Dirac's prediction (Slide 40). The crucial idea of Anderson was to insert inside the Wilson chamber a thin metallic plate which would absorb a fraction of energy of particles passing through it. The historic photograph taken by Anderson is shown in Slide 39 (upper right corner). It can be seen that the single recorded track of a particle of electron mass was moving upwards because its curvature above the plate was clearly larger than below the plate, thus indicating the loss of energy. This fact combined with the known direction of the magnetic field provided the proof that the track was left by a positively charged particle which moved upward, and not by a negatively charged particle moving downward.

In England John Cockroft and Ernest Walton built the electrostatic accelerator and performed the experiment in which accelerated protons collided with the lithium 7 target and produced two alpha particles (Slides 41-42). It was the first nuclear reaction planned and achieved with the use of accelerators. At that time Robert van de Graaf devised another electrostatic accelerator (Slide 43), and Ernest Lawrence built the first cyclotron. The first cyclotron was small, only 10 cm in diameter (in Slide 44 Lawrence is seen holding the cyclotron in his hand) but after a few years much bigger machines have been constructed (Slide 45).

The participants of the Solvay Conference in 1933 had a lot to discuss about the new discoveries. It was the last Solvay Conference attended by Maria Skłodowska-Curie (she died in 1934). Besides her there was also her daughter Irène, and the third woman-physicist, Lise Meitner from Austria (Slide 46).

In 1934 Irène Curie and her husband Frédéric Joliot discovered artificial radioactivity. They observed positron emission after irradiating aluminium with alpha particles from polonium and noticed that it did not cease immediately after removing the source (Slide 47). In the same year Enrico Fermi constructed the first theory of beta decay which included the hypothetical neutrino proposed by Pauli. He and his group in Rome discovered that slow neutrons colliding with nuclei produce radioactive isotopes (Slide 48). During the search for transuranium elements (Slide 49) Fermi mistakenly took his results as the observation of new elements: Ausonium and Hesperium. Mistaken conclusions concerning transuranium elements were announced also by Irène Curie.

Meanwhile in Berlin Otto Hahn, Lise Meitner and their young student Fritz Strassmann were carrying out similar experiments. Meitner was the leader of the group having most experience in the study of nuclear reactions. She was of Jewish origin but converted to Protestantism in her youth. Being Austrian and therefore a foreigner, she could work in Berlin after the Nazi regime expelled all Jews from the state institutions and locked many of them in concentration camps. The situation changed dramatically after *Anschluss*, the forced incorporation of Austria into Germany in March 1938. Meitner's life was now in danger but she managed to escape to the Netherlands and from there to Sweden. At that moment the Berlin experiment which she directed was in the final stage. Meitner continued to give instructions to Hahn by sending letters from Sweden. In December Hahn and Strassman discovered the fission of uranium caused by neutrons. They did not understand the surprising results but at once published experimental data without including Meitner's name, because otherwise their life could have been in danger (Slides 50-51). A few weeks later, in January 1939, Meitner and her nephew Otto Frisch published the correct explanation of the new phenomenon. In 1944 Otto Hahn was alone awarded the Nobel Prize in Chemistry for discovering fission of uranium. Lise Meitner was omitted which was considered as one of the biggest scandal in the history of Nobel Foundation.

The scheme of neutron-induced fission is shown in Slide 52. The transuranium elements have been indeed discovered later, beginning from neptunium and plutonium discovered in 1940 in the USA, up to the element 118 (Slide 53).

Further development of nuclear physics involved building nuclear models (Slide 54). The liquid drop model elaborated by Bohr and Wheeler in 1939 was very efficient in explaining binding energy of nuclei. The shell model developed mainly by Maria Goeppert-Mayer and Hans Jensen took into account grouping of nucleons in separate shells; it served to explain the existence of „magic" numbers of protons and nucleons which resulted in higher binding energy of the nuclei. The collective model developed by Aage Bohr (the son of Niels Bohr), Ben Mottelson and James Rainwater took into account collective motions of nucleons: their oscillations and vibrations.

Cosmic radiation was discovered by Austrian physicist Victor Hess during his balloon flight in August 1912 (Slide 55). It had been noticed long ago that a charged body, e.g. an electroscope, gradually loses its charge apparently because of some unknown ionizing agent in the atmosphere. After the discovery of radioactivity in 1896 it seemed likely that the ionizing radiation came from radioactive substances present in the earth, water and air. Thus, it was expected that the intensity of that radiation should decrease with altitude. Hess took to his balloon sealed electrometers and measured their rate of discharge. To his surprise the rate increased with altitude which suggested the existence of an extraterrestial source of radiation. Hess' result had been confirmed by further balloon flights.

With the discovery of the neutron the existence of atomic nuclei had to be explained by a new, non-electromagnetic interaction between neutrons and charged protons. Japanese theoretician Hideki Yukawa postulated a new theory of nuclear forces that required the existence of a new type of particle, a charged boson with the mass of about 200 electron masses, which could be the agent of charge exchange force. Unfortunately his paper was published in 1935 in a little-known Japanese periodical and remained unnoticed (Slide 56). Meanwhile Carl Anderson and others discovered in the cosmic rays charged particles about 200 times as massive as the electron. The Yukawa paper was soon recovered and his prediction seemed to be fulfilled. However subsequent measurements of the passage of the new cosmic ray particles through the atmosphere showed that their interaction with air was much weaker than required for the postulated nuclear force particle (Slide 57). It led to the suggestion that perhaps there existed two particles of similar masses but different properties. It was confirmed in 1947 by Cecil Powell and his collaborators in Bristol (England) who discovered strongly interacting π-mesons which decayed into weakly interacting μ-particles (Slides 58-59).

After 1947 the physics of elementary particles and processes developed very fast. The discrepancy between Dirac's theory and the measurements of hydrogen energy levels led to creation of renormalized quantum electrodynamics by Feynman, Schwinger and Tomonaga. It is now the most precise physical theory (Slide 61).

In December 1947 Rochester and Butler made a surprising discovery of new particles which appeared to have unusual properties and were found to be produced in pairs (Slides 62-63). Gell-Mann, and independently Nishijima, introduced a new quantum number, which we now call „strangeness" (Slide 64). At that time most physicists had been occupied with the physics of the π-mesons and disregarded „strange particles" (Slide 65). In 1952 Marian Danysz and Jerzy Pniewski, from the University of Warsaw, discovered the first hypernucleus, in which one of the neutrons had been replaced by the lambda-particle, one of the new strange particles (Slide 66). The number of these new particles discovered in interactions of cosmic rays grew rapidly, so that theoreticians searched for some ordering principle. Gell-Mann was again successful in proposing quarks, hypothetical particles with non-integer electric charge, which were supposed to serve as building blocks of protons, neutrons and other strongly interacting particles. However, his proposal met with disbelief and even ridicule (Slides 68-71).

New detectors, in particular large bubble chambers, helped in faster accumulation of experimental data. Gell-Man’s prediction of existence of the „triple strange” omega hyperon had been confirmed (Slides 72-73).

In 1956 two young American physicists of Chinese origin, Tsung Dao Lee and Chen Ning Yang, published a seminal paper concerning the conservation of parity (mirror reflection invariance) in weak interactions. They pointed out that that important problem had never been the subject of experimental study (Slide 74). They suggested some experiments to get the answer to this problem. In Slides 75-78 we find a simple explanation of the experimental problems. Reflection in a mirror reverses the direction of rotation (Slide 75), so that angle α corresponds to angle $180^o - \alpha$ in the mirror world (Slide 76). Radioactive nuclei have their magnetic moments pointing in various directions because of thermal motion (Slide 77), but they could be ordered (Slide 78). Once it is done one has to measure the numbers of radioactive products emitted at angles α and $180^o - \alpha$. The experimenters have found that these numbers were different which meant that parity is not conserved in weak interactions (Slide 79). The news about that discovery appeared even in the daily newspapers.

In the period 1957-1964 the physicists thought that perhaps the invariance existing in nature is a combination of parity P and so-called charge conjugation C which changes the sign of the electric charge (Slide 81). However in 1964 James Cronin and Val Fitch discovered that also the CP is not conserved in weak interactions (Slides 82-85).

In 1956 Fred Reines and Clyde Cowan finally managed to detect the elusive neutrino, postulated 26 years earlier by Pauli. The detection scheme is shown in Slide 86 and the observed signal - in Slide 87. Wolfgang Pauli was still alive and he was very satisfied receiving the historic telegram (Slide 88). It was soon discovered that the neutrino from nuclear beta decay is different from that emitted in the decay of the π-meson (Slide 89). In 2000 the third type of neutrinos was discovered (Slide 108).

There was big progress in construction of powerful accelerators and storage rings. The conventional accelerators became very large and massive (Slides 90-93). The energy of particles accelerated in such machines was only partly available in collisions, because of the centre-of-mass motion. In colliding beams accelerators the centre-of-mass remains at rest, so that all the energy of collision is available for interaction of particles (Slide 94).

By 1955 the accelerators became powerful enough to observe creation of antiprotons (Slides 95-96). Other antiparticles as well as antiatoms have been also produced and studied (Slides 97-100). The experimental study of energy levels in atoms and antiatoms, now under way at CERN, is aimed at checking the properties of matter and antimatter (Slide 101).

In Slide 102 we find the list of the most important experimental discoveries (red) and theoretical concepts (blue) in the path to the present Standard Model, which remains in excellent agreement with all experimental facts in particle physics. We know, however, that it can not be the ultimate theory of particles because too many parameters have to be measured and inserted there from experiment.

The structure of nucleons was first studied experimentally by Robert Hofstadter who measured the charge radius of protons, neutrons and nuclei by scattering medium energy electrons. When higher energy electrons became available from more powerful accelerators it helped to penetrate the nucleons and get information on their internal structure from so-called deep inelastic scattering. Jerome Friedman, Henry Kendall and Richard Taylor discovered that there must be smaller particles inside nucleons. Richard Feynman invented the parton model („parton" from part of the proton). Further experiments showed that the internal structure of nucleons is very complicated: it includes valence quarks, sea quarks, quark-antiquark pairs, and gluons (Slides 103-105). Moreover, the „visible" structure depends on the energy of the probing electrons.

Sheldon Glashow, Abdus Salam and Steven Weinberg have shown that the mathematical structure of the theories of weak and electromagnetic interactions can be unified. The predicted charged carriers of weak interactions, the W^+ and W^- bosons, have been soon discovered, as well as the predicted neutral currents which are mediated by the neutral carrier, the Z^o boson (Slide 106). In 1974 a new particle J/ψ with unusual properties was discovered by two independent teams, in Brookhaven National Laboratory and Stanford Linear Accelerator Center. It appeared to be composed of so-called charmed quarks of the second generation of quarks (Slide 107). The third generation of quarks was postulated by Kobayashi and Maskawa. Their prediction had been confirmed by experiments (Slide 108). In 1989 four experiments performed at CERN independently set the limit on the number of generations of quarks and leptons by measuring the properties of the Z^o boson decay (Slide 109). Thus we have three generations of quarks with two quarks in each generation. In addition, quarks have so-called „colour", the kind of charge, which differs from the electric charge in that it can take three values, and not two; these three possible values are called „colours" and usually named red, green, and blue (Slide 110).

The evolution of our views on elementary particles is shortly summarized in Slide 111. In 1938, just before the outbreak of the 2nd World War, the table of particle which were treated as elementary had only seven entries. In the 1970s there was a proliferation of new particles; in later years „the particle ZOO" was classified and ordered, so that the present list of elementary particles is short: three generations of leptons, three generations of quarks, the bosons - carriers of electroweak and strong interactions, and the Higgs boson H of the universal scalar field pervading space and responsible for masses od all particles. The dates in brackets indicate the year of the theoretical prediction, those without brackets - the year of experimental discovery.

Is this the end of the road?