TOPICAL REVIEW: NUCLEAR PROCESSES

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Summary

The introduction gives a short review of the historical development of nuclear physics. Afterwards, different nuclear processes are commented. The presence of nuclear physics in modern times and its implications are discussed parallel to the description of different phenomena and latest developments in nuclear science. Political efforts in the past to control the nuclear "ghost" and the consequences associated with it are reviewed.

1. Introduction (A Historical Review)

When one talks about the beginning of nuclear physics, not in the philosophical but real, practical sense, then it is the year 1896, when Becquerel discovered by accident the radioactive rays. Henri Becquerel got interested in X-rays, discovered by Wilhelm Conrad Roentgen on November 8, 1895. The X-rays were detected by a fluorescent material and Becquerel thought to test different materials in order to see if they also emit light. When he tested uranium salt he found it emits rays: The uranium salt and a photographic plate were wrapped up in black paper and exposed to the sun. Developing the photographic plate the shadow of the uranium crystal was seen. However he misinterpreted the result, thinking that the radiation was induced by the sun. When he tried to repeat the experiment end of February 26 and 27 the sky of Paris was covered with clouds and therefore Becquerel guarded the covered plate with the uranium salt into his desk. When later on he developed the plate, to his surprise the shadow of the salt piece could be seen. In conclusion, the salt itself must have emitted spontaneously the radiation. Due to this discovery he was awarded with the Nobel price in Physics in 1903, together with Marie and Pierre Currie. Marie and Pierre Curie became famous in discovering various "radioactive" materials, as they are called now.

In 1897 Joseph John Thomson demonstrated that the rays emitted by a cathode are composed by negative charged subatomic particles, called then electrons. J.J. Thomson developed subsequently the first model of the atomic nucleus, known as the "plum pudding" model, where the electrons were emerged in a positively charged sphere.

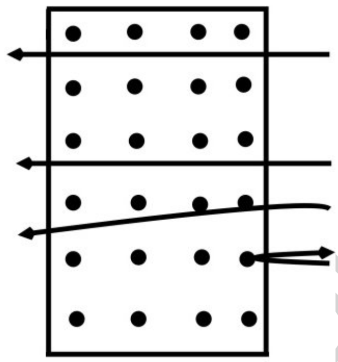

Figure 1: Illustration of Rutherford's experiment. While most particles pass through the block of material, some come near and experience a substantial deflection. In very rare events the particle hits directly a nucleus and is scattered backwards. The experiments demonstrated the most of the matter is concentrated in a small volume represented by the nuclei.

Ernest Rutherford's first important contribution was the distinction between two types of radioactive rays, called α and β. The first type had a less penetrative character than the last. His more famous discovery he made in 1909 when he bombarded a gold foil with a collimated beam of α particles. He expected that most of the α particles go through the gold foil due to their high energy. To his surprise a few were scattered backwards. To understand his reaction, the phenomenon is similar to shooting a gun against a tissue and the bullet is scattered back towards you. The only explanation possible is that the positive charge is concentrated in an extremely small volume (known today to be of the order of 10^{-13} *cm*!) and the electrons are distributed around it.

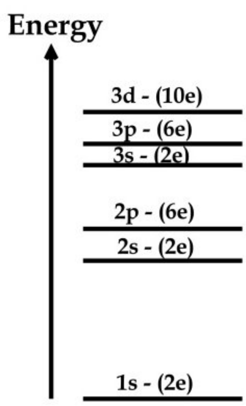

Figure 2: In Bohr's atomic model electrons can occupy certain orbitals only, which carry an orbital momentum, s for zero, p for one and d for two. The number in front denotes the number of shell. In each orbital there is a maximal number of electrons allowed (number in parenthesis).

The main problem with this picture was that the electrons are negative charged particles which emit radiation when forced on curved orbits. The atomic model, proposed by Rutherford, was instable using the known physical laws at that time. The explanation came later on by Niels Bohr who proposed in 1911 a model for the atomic nucleus. In this model the electrons could live only in certain orbits which forbid to decay in lower orbits once they were occupied. The model proposed by Bohr gave a very nice and simple explanation of the observed atomic spectrum, until then only described by certain rules (like the Balmer series). The new theory of the microscopic world, the quantum mechanics developed by Werner Karl Heisenberg and Erwin Schrödinger in the 1920s, accounted for the existence of only particular solutions (orbits) in the atom.

Still the problem maintained of how such a large positive charge could exist in a small volume. Also that the total mass number was not proportional to the total charge and several isotopes existed (these are nuclei with the same charge but different masses) posed a problem. With the invention of the mass spectrometer by F.W. Aston in 1919 it became possible to "weight" nuclei. Aston used a combination of magnetic and electric fields which made it possible to focus on one place of photographic plate particles with the same mass. The precision was high enough (about 0.1 per cent for mass differences and one per cent for absolute masses) to separate different isotopes, i.e., nuclei of the same chemical element but different masses. In a picture of the nucleus where only protons and electrons exist, one assumed that a nucleus of A times the mass of a proton and charge Z times the unit of the elementary charge e (= 1.60210 10^{-19} Coulomb) consists of Z protons and (A-Z) electrons.

Related to this is the "spin paradox" of ^{14}N. Through mass measurements one knew that this isotope has charge number seven and mass number fourteen. If only protons exist, the nucleus has to be composed out of fourteen protons and seven electrons. The protons are needed to get the mass right and the electrons for the net charge. However, protons and electrons have spin $\frac{1}{2}$, i.e. the twenty one particles can be coupled to half integer spin only, contrary to the observed integer spin (1^+, spin one with positive parity). A way out of it, maintaining the conservation of spin, is to propose another nuclear particle with the same mass as the proton but zero charge, i.e. the neutron. Finally, in 1932 James Chadwick discovered the neutron and the modern picture of the atomic nucleus emerged.

Parallel to this development, there existed a paradox in the β decay of the nucleus. The electrons emitted, showed a continuous spectrum. If energy and momentum are conserved, a discrete line should be seen, corresponding to a definite energy equal to the energy released in the decay. To solve the problem, Wolfgang Pauli proposed the existence of the neutrino, a particle which plays an essential role in astrophysics. His proposal was quite unusual: On 4th December 1930 Pauli wrote in a letter to the "Dear radioactive ladies and gentlemen" on occasion of a conference in Tübingen, Germany. He could not attend the meeting because he was "indispensable" (in Zürich on account of a ball, i.e. he preferred to have a party). Calculations showed that for this particle, it must be extremely easy to penetrate large amounts of matter. Only decades later this particle was confirmed by Clyde L. Cowan and Frederick Reines in 1957. The neutron discovered in 1932 was first to be mistaken as the neutrino.

Experimental techniques also improved. Instead of using natural radioactive rays one searched for artificial means to accelerate particles. Increasing the energy the Coulomb repulsion could be overcome between, e.g. the α particles and any atomic nucleus because both are positively charged. The person who succeeded in the construction of an accelerator was Ernest Orlando Lawrence. In 1931 he constructed the first cyclotron for which he was awarded with the Nobel Prize in 1939. From now on it was able to construct larger machines for probing deeper and deeper into the structure of matter.

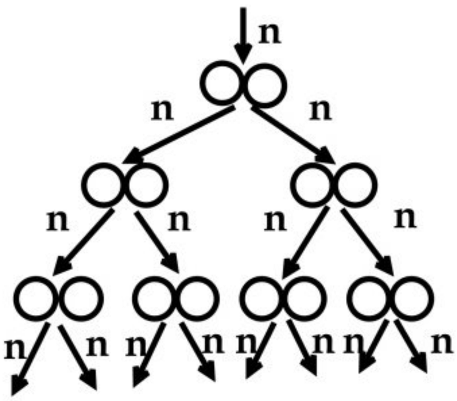

Figure 3: A neutron hits a ^{235}U nucleus and parts it into two nearly equal trunks. During the process two neutrons are set free which on their own can provoke fission in other ^{235}U nuclei, and so on.

It was clear to the nuclear physicists that the atomic nucleus contains a large amount of energy, simply by applying the famous formula $E = mc^2$, deduced by Albert Einstein. However, it was never believed until the 1930's that this energy could be released. In the 1930's an intensive search through all known elements began, in order to see possible mechanisms. The newly discovered neutron served as a projectile because it was electrically neutral and could penetrate into the nucleus without great effort and thus provoking nuclear transmutations. Enrico Fermi was one of the most active scientists in this search. He also bombarded uranium with neutrons, however did not succeed to interpret the experimental results as fission of the ^{235}U isotope. This discovery was reserved to Otto Hahn and Fritz Strassmann in 1938 in Berlin, Germany. Lise Meitner, who had to flee from the Nazi-Germany shortly before the discovery, worked together with Hahn for decades and was crucial in the preparation of the experiment. Lise Meitner and her nephew Otto Frisch published a paper about how this process might happen by assuming that the nucleus can be described as a liquid drop. They interpreted the result of Hahn's experiment as fission of the uranium nucleus, which was explained as a competitive process between minimizing Coulomb repulsion and surface tension.

From that day on, the conversion of nuclear energy into heat became possible. The application ranges from using it as an energy source up to building a bomb. The latter was perused first because the Second World War started and there was a good reason that the Germans could build such a bomb too, especially taking into account the announcement of a wonder weapon (Hitler referred to the V1, a cruise missile, and to the V2 rocket). Indeed, actions for the construction of an atomic bomb were going on in Germany under the guidance of Werner Karl Heisenberg and Carl Friedrich von Weizäcker. Fortunately, they never succeeded, also because the allies bombarded a heavy water factory in Norway, crucial for building a first experimental nuclear reactor.

Heavy water was necessary for the moderation of the neutrons emitted during fission. As it turned out, the slower the neutrons the easier it gets to provoke fission, in which about the two neutrons are released. In the United States the so called Manhattan project started with the intention to design the atomic bomb and use it against the Germans. The scientific leader of this project was Robert Oppenheimer. On December 2, 1942, Enrico Fermi and his group succeeded to maintain the first artificially sustained nuclear chain reaction. The first atomic explosion took place on July 16, 1945, in Trinity, USA.

It was too late to apply the bomb against the Germans because they already surrendered unconditionally. The bomb was used in Hiroshima on August 1945 and short later in Nagasaki. The first was a uranium and the latter a plutonium bomb. Alone in Hiroshima about 140 000 civilians were killed. After that, the world had changed completely! For the first time mankind could destroy itself. As a consequence a nuclear arm race took place between the western block (leaded by the USA) and the eastern block (leaded principally by the now desolved USSR).

Fermi and collaborators thought that they had created the first nuclear chain reaction on earth. However, an interesting natural phenomenon was discovered in 1972 in a uranium mine in the Gabon Republic, West Africa. The place is now known under the name of Oklo. During a sample routine analysis in the French nuclear-fuel processing plant in Pierrelatte a strong depletion of the ^{235}U isotope was found. Normally, natural uranium consists of 0.72% of this isotope. The sample of Oklo contained substantially less (samples were found with a depletion of up to 0.44%!). Investigating in more detail at Oklo one also found the typical residual isotopes of nuclear fission (after having decayed), especially the neodymium isotopes whose masses of stable elements ranges form 142 to 150 in units of nucleon masses. Six of them are nuclear fission products. How this could happen, when a portion of 0.72% of ^{235}U in natural uranium is not sufficient to start chain reaction? The answer is that more than one billion years ago ^{235}U comprised about 3% of natural Uranium. Due to the shorter lifetime of this isotope (700 million years compared to about 4.5. billion years of ^{238}U) most of the ^{235}U nuclei have decayed. With 3% of ^{235}U and water as a moderator, a chain reaction gets possible. This kind of situation was proved to have prevailed in Oklo. Today it is accepted that some 1.7 to 1.9 billion years ago a nuclear chain reaction took place during the order of 150 000 years. The reaction included fission of ^{235}U and breeding reactions of ^{239}Pu. The latter is produced when a ^{238}U captures a neutron and then decays in two steps into

^{239}Pu. Thus, the nuclear chain reaction of the nuclear reactor, constructed by E. Fermi and his group, was not the first on earth! It was the first artificial, man made nuclear chain reaction on earth! Maybe in other locations such processes happened too. The importance of this finding lies in the fact that nature provided us with a long term experiment on how nuclear reaction products are contained over the eons in the soil. The result is very promising, indicating a very low diffusion or none of these elements through the soil.

After the Second World War a division in nuclear physics took place: The field got divided gradually into what is known by now as particle physics, field theory and nuclear physics. In fact this division partially started already in the 30's when first attempts were made to create a quantum theory for the electromagnetic interaction. Due to larger accelerators after the war, more and more particles were found calling for a different concept to the notion of elementary particle.

Nuclear physics itself became more complex. One particular area was founded in 1938 by H. Bethe who demonstrated that the power of the sun has its origin in the nuclear fusion process, where proton fuse via several steps into helium atoms emitting during the process other particles like electrons and neutrinos. This work initiated a whole area called "Nuclear Astrophysics" which maintains nowadays a very close relation to astrophysics and nuclear structure.

Nuclear structure physics describes the spectroscopy of the nuclei. Because the nucleus is a very complicated many-body problem approximations have to be applied. One is the "mean-field" approach where the interaction between nucleons is approximated to lowest order by an average potential. The most famous one is the spherical shell model proposed by Maria Goeppert-Mayer and independently by Hans Jensen in 1948. From there a whole new field of structure physics evolved: Nuclear shell model calculations starting from a microscopic two body interaction, extended models like the deformed shell model by S.G. Nilsson and symplectic models.

However, treating even in the shell model a system of many nucleons did lead to extremely technical difficulties. Another approach was used, namely the description of the nucleus as a liquid drop. In 1935 C.F. Weizäcker developed the liquid drop model of the nucleus for the description of systematics in the binding energy of the nuclei. His mass formula is still accurate and helped to understand the energetics in nuclear reactions. A more complete description of the liquid drop and its excitations, within a quantum mechanical picture, was made possible by A. Bohr and B.R. Mottelson. The achievement lies in demonstrating how to quantize the Hamiltonian (an operator giving the energy when applied to a quantum mechanical state) which describes quadrupole deformations (something like ellipsoidal shapes) of the nucleus.

Both models, liquid drop and the shell model, and related theories, existed parallel for a couple of decades until the first attempts were made to connect them. Here the symplectic shell model provides a relation to the nuclear deformation variables. Potentials were derived and calculations performed in the geometrical model which provided the first direct connection between a shell and a geometrical model.

Another big area in nuclear physics is related to the description of nuclear reactions. An important step forward was achieved due to the R-Matrix formulation of nuclear reactions. The theory consists essentially in dividing the space in an area where nuclear reactions are effective and another one where the collision participants are moving apart, only experiencing the Coulomb force. The solution of the problem reduces to implement correctly the boundary conditions between the two spaces. Today any student has to learn in Quantum Mechanics the simplified form of the R-matrix theory, e.g., when in one dimensional description the wavefunction, in the presence of a potential restricted to a finite part of the space, has to be determined. The R-matrix theory belongs nowadays to the standard technique in describing nuclear reactions.

In 1960 D.A. Bromley et al. discovered the existence of nuclear molecules. These objects consist of two nuclei which stick together and form a system similar to the two atomic molecules. The binding is provided by nucleons in the valence orbitals. This topic has given rise to a huge amount of papers known in general as cluster studies and is still a very active field. For a comprehensive summary the book about the nuclear molecules in the list of references is recommended. A very intense topic in this field has emerged during the 1990s when cluster radioactivity was predicted and discovered. Recently the physics of nuclear molecules experiences a great surprise when long living nuclear molecules, consisting of three clusters were discovered by the group around J.H. Hamilton from Nashville, USA. Normally a nuclear molecule lives ten times the collision time of two nuclei, which is of the order of 10^{-22} seconds. The molecule observed consists of a ^{96}Sr and a ^{146}Ba nucleus with a ^{10}Be nucleus probably in between, which provides the binding. The lifetime is of the order of 10^{-13} seconds or larger, an eternity in nuclear physics! Two further systems were identified later on. This opens up, for the first time, a spectroscopy of nuclear molecules which had not been possible before.

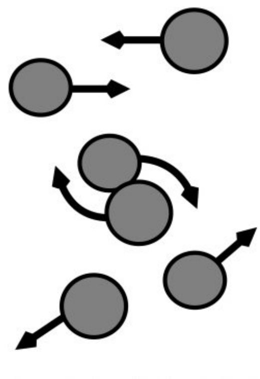

Figure 4: A nuclear molecule can be formed when two nuclei collide in such a way that they maintain their identity through the time they stick together. Such events generate structure in the observed cross section through which the molecules are identified.

In the seventies the nuclear physics community approached again into the direction of particle physics. Accelerators for heavy ions were available, like the one in Brookhaven (near New York, USA), GSI (near Darmstadt, Germany), Berkeley (near San Francisco, USA) and many more. For the first time it was possible to smash the nuclei with such a high energy together that new types of matter could be created. One hope is to produce for a short time the situation which had prevailed at the mere beginning of the universe, the big bang. The types of matter, which one hopes to form, might contain the so-called quark-gluon plasma. This is a state where the quarks, anti quarks and gluons, which form the main constituents of matter known today, are no more subjected to confinement but can move freely. From first intents on in the seventies this field has developed to the most active one in nuclear physics.

Though, there had been times when nuclear physics was called dead, it is still very active and provides links to various different fields in physics, like astrophysics and particle physics. Nuclear physics is sometimes indispensable, like in the description of double beta decay, where the structure of nuclei has to be known as good as possible, and the neutrino problem of the sun. The double β decay enjoys an active interest in the last ten to fifteen years. During the process two neutrons are converted into two protons. On the way two electrons and two anti-neutrinos are emitted. This process is of second order and has a very low probability to happen. It is only observable in nuclei where the ground state of the intermediate nucleus lies higher than the initial and final one. These nuclei have half lives of the order greater than 10^{20} years! There is another type of double β decay, predicted when neutrinos have mass and are also Mayorana particles (which are their own anti-particles). Then no neutrinos are emitted but only electrons. The implication of such a discovery would be tremendous because it implies a mass for the neutrinos and shows violations in the basic assumption of the standard model of elementary particles. The search is on the way in several laboratories in the USA, Japan and Europe.

Also new topics emerged recently like the extension of the nuclear chart to strange nuclei (they carry the strange quantum number like the Λ resonances). Also there is a search for whole anti-nuclei produced in ultra relativistic heavy ion collisions.

After having given a rough review of the historical development of nuclear physics, from the past to the present, and an idea of the onset of the future, in the next section different nuclear processes are commented. When the reader is interested in more details of the historical development of nuclear physics, until to the construction of the atomic bomb, the excellent book by Richard Rhodes is recommended (The making of the atomic bomb) awarded with the Pulitzer Prize.

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