Nuclear reactions, unicity of matter and mass. From Thalès to Einstein [?].

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[?] Thème de la chaire Francqui au titre belge 2005-2006

Nuclear reactions are presented from the perspective of their historical connection with two long-lasting problems in Physics: unicity of matter and conservation of mass. Their importance as the energy source for life is underlined. A short overview of the present status of the field is given.

Introduction

Nuclear reactions offer a fascinating topic for, at least, three reasons. First, their discovery and early investigations appeared as a climax in a long historical debate about unicity of matter, that started twenty-seven centuries ago and which is not yet closed. This debate is profoundly rooted in the development of natural philosophy and perhaps of philosophy itself. Second, nuclear reactions may be accompanied by a large release of energy. In this respect, they may be not only fascinating, but also frightening. This aspect is related to another long-lasting problem, the conservation of mass. It may even be linked with another still open question, the meaning of mass itself. The third reason of fascination is somewhat more surprising since it is known by everybody, but is not perhaps always evident to everybody's mind. I mean the fact that the real motor of life on Earth, the real source of energy, is powered ultimately by nuclear reactions occurring far away, in the interior of the
Sun.

I will elaborate on each point successively, putting them in an historical perspective.

Nuclear reactions and the unicity of matter

This first point brings us back to ancient Greeks and to the birth of philosophy. Around 640 B.C., Thalès of Milet and his colleagues were concerned with the changes in our world, in our environment. This reflection always amazes me, because every time I go to Greece, I have the opposite impression, i.e. that the landscape should have always been the same. In any case, the ancient Greeks should have been puzzled by simple observations of transformations, such as the transformation of ice into water, or the transformation of wood into flame in an open fire. They tried to find a coherent (we would perhaps call it rational) explanation to all these changes. They did not limit their reflection to what we call the mineral or inanimate world as we might think. They did not really distinguish between the living world and the rest and they arrive at striking questions, such as: “How water and soil can transform into a frog?”

It is then not surprising that the early philosophers tried to explain the changes by including life or spirit as motors or causes of changes. Sometimes they even appeal to human feelings, as love and hate. Nevertheless, this is the way they started philosophy, and in some sense, science. The Greek philosophers indeed tried to find explanations that are based on logic and reasoning, rather than on belief and myths.

Progress were slow until Empedocles (504-450 B.C.), who was also a Greek but living in Agrigente, Sicily. He considered that the world is made of four elements (air, water, fire, earth) and that the observable changes are due to mixing (rather than transformation) of the various elements. In his theory, changes were determined by the relationship between Love (Eos) and Hate (Polemos) .

Then came Democritus (~460-360 B.C.) of Abdere who, inspired by Leucippe, proposed the atomistic theory. According to him, matter is not continuous. It cannot be divided indefinitely. It is made of small entities, the atoms, separated by or moving in vacuum. The atoms are solid and have a dimension escaping from our senses. They are creepy, spiky, smooth…, attributes that can explain the properties of specific macroscopic materials. They cannot be modified. They move and combine to form various compound materials, including the four elements of Empedocles. Democritus introduced also the concept of conservation of matter: “Nothing comes from the non existing [vacuum] and nothing returns to it”.

The atomistic theory of Democritus, which will be confirmed so triumphantly twenty-four centuries later, was not easily accepted by the philosophers of his time and was even ridiculed by some of them. The final strike was given by Aristotle (384-322 B.C.), who disliked Democritus's theory for several reasons. He did not like the vacuum[1], but the most important reason is that Aristotle privileged what can be tested by our senses. In his mind, any concept which does not deal with what can be observed has no real usefulness and even no meaning. Democritus’s theory was plainly under this criticism, since it introduced for the first time the explanation of the macroscopic world by microscopic objects and properties. It is interesting to note that Democritus anticipated this criticism by saying that “it is the simplest explanation for the observed changes in Nature”, an argument close to Occam’s razor[2], which played an important role much later in the development of theories in physics.

Aristotle revived Empedocles’s theory of the four elements, but admitted that they can transform into one another and that they can even disappear. He also claimed that the matter is responsible for the shape of the objects and for their changes.

The debate remained more or less unsolved, because, in fact, there were no real manner to test the theories. As Lenoble remarks, “L’atomisme n’a jamais eu un seul fait à se mettre sous la dent » (Atomism has never had a single « data » to confront with)[1] . As a matter of fact, Aristotle’s doctrine prevailed for a long time, until the sixteenth century and atomism was simply forgotten for more than twenty centuries.

The question of the changes of matter was resumed in Europe around the 13th century by the alchemists. The origin of alchemy is rooted in the study of metallurgy, but developed in the Middle Ages in a strange way. Alchemists were definitely interested in the changes of matter, including among the four elements of Empedocles. But they introduced two other important components in their discipline. First, they consider that research on matter (« the laboratory ») had to be paralleled by a constant improvement of their mind, of their intellect, of their wisdom (« the oratory »). It seems that the second goal was even more important that the first one[2]. The second aspect may appear as a monstrosity to our ethics of modern scientists. The alchemists developed a real science, but never conveyed it in a transparent way.

1 Incidentally, this led Aristotle to invent the existence of the quintessence (literally the 5th element), which, like its derived concept of aether, was supposed to pervade all space, opening so another long-lasting question, which will be clarified by Einstein.

2 W. Occam, Franciscan friar, 14th century; Occam's razor principle is: ``Entities should not be multiplied unnecessarily'', often rephrased in modern language as ``When two competing theories make exactly the same predictions, the one that is the simpler is the better''.

It was, rarely, encoded in hermetic manuscripts. They also considered that their science should not be disseminated into the public. It should be kept to circles of persons prepared to receive it and to use it in a beneficial way. The transmission of their knowledge was therefore realized on the master to (single) disciple basis. This mode survived in other fields of activity, perhaps in a more flexible way, until the beginning of the last century.

Concerning their study of matter, alchemists introduced a notion which may appear weird to us, but which is not totally removed from our considerations about the inanimate world: they distinguished between base and noble matter. The popular belief is that they may have been able to transform base metals into noble metals, for instance to transform lead into gold, preceeding so by five centuries what will be doable with modern nuclear technology. There is little doubt that this is a legend, inasmuch as it is even easier to transform lead into gold than the reverse with modern nuclear means.

Nevertheless, alchemists can be credited with the discovery of many substances and many techniques, such as distillation. Alchemy declined since the 16th century and leaved progressively the place to chemistry, which at the beginning was closer to the art of preparing various medicines, materials, cosmetics, and so on, than to science[3]. Nevertheless, an intense and painstaking activity was deployed in Europe and at the end of the eighteenth century, chemists arrived at a consistent picture of matter. They recognized that most of materials are mixtures of pure substances and they succeeded to isolate many of the latter. From instance, air is mainly a mixture of oxygen and nitrogen, ores are mixtures of salts, oxides and metals, etc. To make it simple, pure substances appear as matter with homogeneous and specific properties. The chemists also realized that pure substances do not have all the same status. Some are more "elementary" than others. A pure substance such as oxygen or copper is an element. A pure sample of water, on the contrary, can be decomposed into hydrogen and oxygen, two elements. A pure substance, which is not an element, such as water is called a compound. The difference between a compound and a mixture is that the properties of a compound have little resemblance with those of its elements: salt is indeed quite different from sodium and chlorine. On the contrary, mixtures generally retain, to some extent, the properties of the ingredients. In addition, the composition of mixtures can be varied at will. If we mix a little of nitrogen with oxygen, the gas mixture will behave roughly like oxygen, maintaining for instance a violent fire. If we mix a little bit of oxygen with nitrogen, the gas will behave essentially like nitrogen and can extinct a candle. The same is true for mixtures of compounds.

At the beginning of the nineteenth century, chemists had identified 50 to 60 elements (there exist actually around 90 of them) and these elements can be combined in a huge variety of compounds. The matter around us appears rarely as samples of pure elements or pure compounds, but as mixtures of them. If one thinks a little bit

3 The birth of chemistry can be attributed to Georg Stahl (1660-1734), who showed than the transmutation of mercury into red needles (oxide of mercury) was indeed a combination of the two elements mercury and oxygen. Chemistry however continued for some time to use wrong ideas from alchemy, such as the phlogistic.

about it, the result at which the chemists arrive does appear as a tremendous achievement, since the differences between mixtures, compounds and elements are rarely as clear-cut as I have explained here.

By sorting matter into elements and compounds, chemists realized chemical reactions: by some processes, elements combine to form compounds, such as

Oxygen + hydrogen ? water

or compounds react to form other compounds

copper oxide + sulphuric acid ? water + copper sulphate

The chemists arrived at a great simplification of our world: some tens of elements can be combined to form a large number of compounds and compounds can be transformed into others by chemical reactions.

It is the time to mention the great figure of Antoine Lavoisier (1743-1794). Among many other discoveries, he showed that in chemical reactions, mass (or weight) was conserved, which he expressed in this famous citation: “Rien ne se crée, rien ne se perd” – “Nothing is created, nothing is lost”. Lavoisier arrived at this conclusion by extraordinarily precise experiments for his time.

Lavoisier has also given the final blow to the theory of the four elements, still followed by some chemists at that time, and to alchemy by claiming authoritatively (rather than demonstrating) that any element cannot be transformed into another one.

Then came John Dalton (1766-1844), a famous man for various reasons. He wrote the first article on colour-blindness, from which he himself suffered. But for our purpose here, he is the man who revived the atomistic theory. He discovered the law of multiple proportions: couples of elements when reacting to form different compounds always enter with weights in simple proportions. As an example, in the reactions

carbon + oxygen ? carbon monoxide
carbon + oxygen ? carbon dioxide

the proportions in weight is always in the ratio 6/8 in the first case and 6/16 in the second case. Similar observations were done for reactions between compounds. From these observations, Dalton concluded that this could simply be explained if elements are made of small entities, the atoms (with commensurable weights) that gather in simple proportions to form molecules when elements react to generate compounds. With this view, we write the above reactions as[4]

4 Here, I deliberately consider oxygen in atomic state, to simplify the presentation. Ordinarily, these reactions are realized with molecular oxygen. Incidentally, it is worth to mention that the molecular state of oxygen, hydrogen, etc, was not known at the time of Dalton. This will be discovered later by Avogadro.

$$C + O ? CO$$
$$C + 2 O ? CO_2$$

Although Dalton's theory can be considered as the act of birth of modern atomism, it seems that Dalton was convinced of the existence of atoms through his study of the physical properties of gases.

The microscopic world thus appeared very simple: a few tens of different atoms typical of so many elements can combine to form molecules and chemical reactions just appear as binding atoms together or as a mere rearrangement of atoms into molecules, like in

$$Hg + O ? HgO$$
$$2 H_2 + O_2 ? 2 H_2O$$
$$Cu_2O + H_2SO_4 ? Cu_2SO_4 + H_2O$$

Dalton enunciated (like the ancient Greeks) that the atom was unbreakable. But in 1897, sir J.J. Thomson (1856-1940) discovered the electron, demolishing this view. Atoms, being electrically neutral, then appeared to be made of electrons and of a positively charged entity. In the same year, Henri Becquerel (1852-1908) discovered what we call radioactivity, by which some substances emit ionizing radiation. It took some time to the physicists to realize that this phenomena was not a property of the atoms considered as a whole, but of some intimate part of them. The answer was finally given in 1912 by Ernest Rutherford (1871-1937), who performed convincing experiments supporting the idea that atoms were made of a positively charged, heavy and tiny nucleus, and of electrons orbiting around the nucleus. Atoms of different elements have different nuclei.

On about the same time, Rutherford and others made two important discoveries. They first realized that in radioactivity, the nature of the elements is changed: a radioactive nucleus is transformed into the nucleus of another element (ex.: U atom ? Th atom). The dogma that the "atoms cannot be corrupted" was splashed down and physicists somehow revived the notion of base (radioactive, unstable) versus noble (stable) matter. They indeed introduced for a while the term "metabolous matter" for radioactive material[3]. Second, Rutherford himself, realized the first nuclear reaction in the laboratory, which can be written

nucleus of helium + nucleus of nitrogen ? nucleus of oxygen + nucleus of hydrogen

So, both in radioactivity and in nuclear reactions, elements can be transmuted into each other (this was indeed the first time "transmutation" was used in microphysics). Thereafter, I will consider both phenomena together.

The nature of the atomic nuclei was still a mystery. It remains so until the discovery by James Chadwick in 1932 of the neutron, a neutral particle with about the same mass as the proton, the nucleus of the hydrogen atom. This allowed an extraordinary simple view of the matter: nuclei are made of protons and neutrons and nuclear reactions are just a rearrangement of neutrons and protons inside the nuclei.

As an example, the reaction above can be written

$$(2\ p, 2\ n) + (7\ p, 7\ n)\ ?\ (8\ p, 9\ n) + p$$

that nuclear physicists use to write as

$$^{4}He + {}^{14}N\ ?\ {}^{17}O + p,$$

which conveys the same information about the nucleon content. Ultimately, our material world[5] appears in an amazing simplicity: it is made of only three particles: proton, neutron and electron. Nuclei and atoms are various arrangements of these building blocks. Nuclear and chemical reactions are simply rearrangements of protons and neutrons, and of atoms, respectively. The mechanisms leading to these rearrangements may be complex, but the results of reactions, be then nuclear or chemical, are amazingly simple.

Although this is in some sense outside the object of these lectures, I cannot omit to mention that unicity of matter applies also at an even smaller scale. Nucleons and other similar particles that can be created in the laboratories, known as hadrons, are composed of quarks. Reactions among them also appear as a mere rearrangement of quarks. However, there are strong differences with chemical and nuclear reactions. First, quarks cannot be extracted from hadrons. The following reaction

$$\text{proton}\ ?\ u + d + d$$

similar to

$$HCl\ ?\ H + Cl$$

in chemistry, cannot be realized. When a quark sitting into a hadron is tentatively expelled, there is automatically creation of a pair quark-antiquark (the antiquark being the antiparticle of a quark), followed by the rearrangement of the quarks, like in the $\Delta^{++}\ ?\ ?^{+} + p$ process (illustrated below) or in the $p+p\ ?\ p + n + ?^{+}$ process.

In these kinds of reactions, it is the number of quarks minus the number of antiquarks that is conserved. Another difference with atoms and nuclei is that the quarks that we

5 For a long time, the possible unicity of matter was restricted to the material on Earth. The first indication that the rest of the World is made of the same matter as on our planet was given by Herschel who observed in the sunlight the lines of hydrogen and some other elements (See Ref. [4] for an interesting review of the subject). It should be mentioned that presently the unicity of matter in the universe is challenged by the possible existence of dark matter (See Ref.[5] for an introduction to this question).

can “visualize” or count in reactions (those that are indicated in the figure above), are only a part of the hadrons. The latter also contain other components (the sea) that we do not understand completely.

Nuclear reactions and conservation of mass

Nuclear reactions are remarkable because they can produce large amounts of energy. This is particularly clear when one compares a typical chemical reaction, such as the combustion of methane

$$CH_4 + 2\ O_2\ ?\ CO_2 + 2\ H_2O$$

with neutron-induced fission

$$n + {}^{235}U\ ?\ 2 \text{ fission fragments.}$$

The first reaction generates 890 kJ per mole (about 12.000 cal per gr of CH_4). The second reaction unleashes 20 TJ (20×10^{12} J) per mole. The energy released per gr of fuel is two hundred thousand times larger in the second case. Not all nuclear reactions are prone to realize production of energy on a macroscopic scale, even if they are exothermic. In similarity with chemical reactions, many nuclear exothermic reactions require the equivalent of an activation energy. Indeed nuclei are positively charged. In order to put two nuclei in close contact, it is necessary to provide them with sufficient kinetic energy to overcome the Coulomb repulsion. This is usually done by creating beams of charged particles with an accelerator. For this reason, charged-particle induced reactions are not really suited for production of energy. Only neutron-induced reactions of the type mentioned above are convenient for that purpose.

It is natural nowadays to discuss the relation between the large energy production in nuclear reactions and mass conservation. Remember that Lavoisier had formulated the rule of conservation of mass in chemical reactions at the end of 18th century. This was considered as a principle until 1905, when Einstein (1879-1955) challenged it. In this “annus mirabilis”, Einstein published five papers, each of them producing a decisive breakthrough. In June, he published a paper which set the basis of special relativity. Einstein showed that the constancy of the velocity of light implies that time is not running the same for observers who are in uniform motion relative to each other. Of course, this new transformation of time (and coordinates) had the consequence that Newton’s law had to be modified. In particular, Einstein deduced that the relation of the kinetic energy T of a body to its velocity v should be modified as

$$T = \frac{1}{2} m v^2 \rightarrow T = mc^2 \left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right)$$

Velocity of light then appears as a limiting velocity for which the kinetic energy approaches infinity.

In September, Einstein published a second paper on special relativity, presented as a consequence of the first one. In a very nice argumentation, using the transformation derived in the previous paper, he showed that if a body emits some radiation of energy ?E in its rest frame, its mass will decrease by an amount ?m, related to ?E by

$$\Delta m = \frac{\Delta E}{c^2}$$

establishing the “equivalence” between mass and energy. This is close to the famous

$$E = mc^2$$

equation, known by everybody. The latter will appear a few years later only and will take full meaning more than 20 years later, when processes by which the mass of particles can be entirely converted into radiation will have been discovered. There are philosophical questions beyond the equivalence between energy and mass embodied by these formulae[6]. In any case, according to special relativity, energy and mass are no longer conserved separately, as believed previously. Only mechanical energy plus mass energy is conserved.

In his paper of 1905, Einstein himself suggested that his theory could be tested “with bodies whose content in energy vary in large proportions (for example with radium salts)”[7], i.e. with radioactivity. He did not refer to chemical reactions, probably because he had realized that the change of mass during these reactions, violating Lavoisier’s principle, is too tiny to be measured. If one takes the example of the combustion of methane, as above, the change of mass amounts to

$$\Delta m = \frac{|\Delta H|}{c^2} = \frac{890\ kJ}{\left(3\times 10^8\ m/s\right)^2} = 10\ n\ gr$$

per mole, which could not be measured at that time and which is probably not measurable even today. Actually, the first verification of Einstein formula was done in 1932 by Cockroft and Walton, who constructed the first accelerator of particles and realized the first nuclear reactions with such a device. In the very first experiment, they could measure carefully the kinetic energies of all particles in the reaction

p + ^{7}Li □ ? + ?

Using the known masses of these particles, they could verify the ?E = ?m/c^2 relation with an accuracy of better than 1 % [8]. For the sake of the anecdote, masses of many nuclei had been measured earlier by Aston and others in the 1920’s or earlier, with magnetic spectrometers. Therefore, the decrease of the mass in this reaction was known before 1932. However, before the construction of the first accelerator, nuclear reactions were realized and studied with the help of radioactive sources (mainly of ?-particles), but these sources were not monochromatic and it was not possible to make this check.

I would like to discuss the link between Einstein and the discovery of nuclear fission, and its consequences on the development of the atomic bomb. I heard many false or equivocal statements concerning this point during the just finished World year of physics, celebrating the 100th anniversary of Einstein's golden year. Quite often people connect the $E = mc^2$ equation, which embodies the liberation of energy from mass, with the discovery in 1938 of neutron-induced fission by Otto Hahn (1879-1968), and its subsequent developments, the Manhattan project leading finally to the Hiroshima catastrophe, which are presented as the most striking illustration of Einstein's famous equation. They often claim that the discovery of nuclear energy was made possible by the discovery of the mass-energy equivalence and sometimes attribute the fatherhood of nuclear energy to Einstein: "$E = mc^2$, the equation that changed the world, leading to the discovery of fission, the atomic bomb and nuclear energy".

In fact, there is no doubt that the fission energy is a physical consequence of the mass-energy relation, but I want to argue that the discovery of the first one is rather independent of the discovery of the other one. It should be reminded that the mass-energy equivalence has not been accepted immediately by the physics community. For many years, it was just considered, at the best, as an hypothesis by a majority of physicists. During this time, nuclear physics developed slowly but rather independently of Einstein's discovery. Nuclear physicists battled hard to uncover the main properties of the nuclei. Einstein was probably aware of the developments of nuclear physics, but paid only little attention to them. As a matter of fact, he never published a paper on nuclear physics. The construction of the first accelerator was motivated by further studies of nuclei and nuclear reactions. It is almost an accident that the first experiment led to the verification of the mass-energy equivalence. At about the same time, the neutron was discovered and nuclear physicists wanted to study nuclear reactions induced by the new particle. This activity eventually led to the discovery of fission. These short considerations indicate that the link between Einstein and nuclear fission is rather loose. In fact, I am convinced that fission would have been discovered in any case, even if Einstein did not publish the article on mass-energy equivalence. He himself acknowledged this conclusion, saying in 1953: "I do not consider myself the father of the release of atomic energy" [9].

The link between Einstein and the nuclear bomb is more involved, but does not either belong to the sole intellectual relationship generated by connected researches. Let me recall a few facts. Fission has been discovered in 1938. Soon after, the possibility of having a chain reaction due to the neutrons emitted by fissioning nuclei is advanced by Joliot-Curie in Europe, Fermi and Szilard in the U.S. The concept of a nuclear weapon of tremendous energy is rapidly put in evidence[6].

6 The first reactor was built by Fermi and his team in 1942. The short time span between the discovery of a physical process and its first large scale application is quite remarkable.

Frightened by the perspective that the Nazis could build such weapons, Szilard, Wigner and Teller approached Einstein in 1939 and urged him to write to President Roosevelt in order to draw this threat to his attention and to invite him to launch a program to build the bomb before the Germans. After some reticence, Einstein accepted and wrote a letter to Roosevelt on the 2nd of August, 1939. The common belief (the myth) is that Einstein contributed reluctantly to the atomic bomb project and its consequences only by this writing, initiating a project that he disapproved anyway. This myth is reinforced by the past anti-militarism of Einstein, especially during the first World War, and by the fact that he signed the Russell-Einstein Manifesto, two days before his death, which led to the foundation of the Pugwash movement [10] against nuclear weapons.

The situation is more complex. First, Einstein did some limited research on the early study of nuclear weapons, but he did not participate to the Manhattan project. He actually sent three, and not only one, letters to the President between August 1939 and April 1940. Einstein did not oppose to the military use of nuclear power. After the first bombing (on Hiroshima), he changed mind and refused to endorse, for himself and for scientists, the moral responsibility of bombing. But he did not criticize the involvement of scientists in the conception of the bomb. Even in 1953, he said: “The discovery of nuclear chain reactions need not bring about the destruction of mankind any more than did the discovery of matches”[11]. Afterwards, Einstein expressed a clear opposition to nuclear weapons. In conclusion, in this historical drama, Einstein was not really an outsider involved by accident. In my opinion, he rather appears as a hero of tragedy, conscious that destiny and duty have to force him to act against his heart and that he could not escape it. At the end of his life, he declared: “I made a great mistake in my life, when I signed the letter to President Roosevelt; but there was some justification: the danger than the Germans would make them.”[12]

Nuclear reactions as the motor of life

The third reason for which nuclear reactions are fascinating is the fact that, ultimately, life on Earth is powered by nuclear reactions. It is indeed nuclear reactions transforming hydrogen in helium in the centre of the Sun, which makes the Sun shine. We still do not understand how life appeared, but we know that there would be no life, at least in the forms we see around us, without the energy coming from the Sun. In this case, the numbers are also and really fascinating. Every second, more than 600 millions of tons of hydrogen are transformed into helium in the Sun, releasing a power of $L_{\odot} = 3.85 \times 10^{26}$ W. Only a very small fraction (40 parts in a billion) reaches the Earth and only 0.023 % of the latter (which nevertheless amounts to 1 TW) is used to power living bodies, through photosynthesis. There are many transformations of the energy between hydrogen combustion and energy processes in living bodies, but the evidence is there: life could not exist on Earth without the energy-producing nuclear reactions deep inside the Sun.

Nuclear reactions have shaped our world

Even if it is less fascinating, nuclear reactions have shaped and are still shaping our world. As already said, nuclear reactions determine the energy that we receive from the Sun. But nuclear reactions are also largely responsible for the quantitative composition of the matter in our Solar system and, to some extent, for the composition of matter on the Earth. At the beginning of the Universe, during the first three minutes, nuclear reactions (and decays) produced the primordial matter, which was made of hydrogen and helium with little traces of only few other elements. This primordial matter agglomerated in early stars. Inside the latter, nuclear reactions produced heavier elements. Matter was ejected from these early stars and ultimately formed other stars, including our solar system and our Sun. As a matter of fact, all the matter around us and even us have been made inside a star. By the same processes, nuclear reactions determine the life and the lifetime of stars and galaxies.

Cosmic rays coming from space contain mainly high energy protons, with an average energy of about one GeV. They produce reactions in the upper atmosphere, which so protects us partly against this cosmic rain. However, secondary less energetic particles, primarily muons and electrons, reach the surface of Earth. Every second, three or four of these particles cross the body of each of us. Cosmic rays are also responsible for part of the natural radioactivity. By nuclear reactions on the molecules of air, they generate the famous ^{14}C which is responsible for the half of the natural radioactivity of our bodies.

Radioactive decays of ^{235}U, ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb in rocks contribute significantly to the heat flow coming from the inside of the Earth. The flux is quite modest, 0.09 W/m^2, 10.000 times smaller than the energy flux coming from the Sun[13]. But, due to the low conductivity of the rocks, temperature raises rapidly with increasing depth below ground level. Ultimately, this energy source is the motor of the Earth tectonics, contributing to make Earth a ever-changing planet, with orogenesis, volcanism, tsunamis and climate. Without the just mentioned radioactive decays, these phenomena would be rather attenuated, if not suppressed.

An overview of the field

Description of nuclear reactions

If the net effect of nuclear reactions, rearrangement of nucleons, is simple, the mechanisms of nuclear reactions are rather complex. We have a single theoretical framework (namely formal collision theory, which also applies to atomic or particle reactions and whose development has largely been stimulated by the study of nuclear reactions), but we do not have yet a single tractable theory. The reason is that nuclear reactions may involve very few degrees of freedom as well as all degrees of freedom and any intermediate situation. Instead, we have several theories for several conditions of energy. Furthermore, at low energy, nuclear reaction cross sections are dominated by numerous narrow resonances, corresponding to quasi-bound states extending the bound state spectrum of the nuclei. To predict the parameters of an individual resonance is practically impossible. But theories exist for the average properties of the resonances and for the average cross sections. Above a few tens of MeV, the cross sections are less sensitive to the details of the nuclear dynamics. I will speak about recent developments showing that we are approaching to a single theory for energies ranging from a few tens of MeV to a few tens of GeV.

Applications of nuclear reactions

Applications of nuclear reactions are very numerous. They condition our everyday life. This is more than just an expression for us, in Belgium, since 55 % of our electricity is of nuclear origin. Besides energy production, nuclear reactions are used to produce new isotopes, stable or radioactive. The latter are used in many fields: medical diagnosis (allowing doctors to "see" inside the body without surgery), medical therapy (especially of cancer), environmental science, by use of radioactive tracers (example: ocean circulation), water resources, security control, pollution control, engineering (new materials with controlled implementation), material analysis, archaeology and art, to enumerate the most well-known examples.

I will spend some time on two recent applications. The first one is called proton therapy. Irradiation of tumours is usually done with ?-rays or electrons. The utilisation of high-energy protons (more than 100 MeV) or of heavier nuclei allows to deliver the dose to the tumour with much greater precision, without touching the neighbouring tissues.

The second application deals with transmutation of nuclear waste. Burned fuels removed from reactors are highly radioactive with elements of very long lifetimes. The idea is to use suitable nuclear reactions to change long-lived elements into short-lived ones (or stable ones). The world "transmutation" is totally adequate here. This operation could be done in various ways. A promising technology rests on so-called accelerator-driven systems (ADS)[14]. In such devices, high-energy protons bombard a spallation target inside a subcritical reactor. Many neutrons are emitted by the spallation target. They are multiplied in the core of the reactor and can transmute radioactive waste inside the reactor. I will also say a few words about alternative ways to cope with the waste problem, in particular about the so-called Generation-IV reactors. I will also make a survey of the general World energy problem and of the other issues of nuclear energy in the future.

Contributions to fundamental physics

First of all, nuclear reactions have helped to study the spectroscopy of the nuclei and the main facets of the nuclear dynamics: the validity of the nuclear shell-model, the Fermi liquid nature of the nuclei, their collective excitations, the various isomerisms, etc. In addition, nuclear reactions have allowed to test more fundamental theories. A well-known example is provided by the V-A theory of weak interactions.

In these lectures, three other more recent examples will be given:

1 High-energy collisions between heavy ions may generate small samples of what we call the quark-gluon plasma, replicating perhaps the conditions of the Early Universe. The existence of such a state of matter, in which quarks and gluons are moving more or less freely, is the main non-perturbative predictions of the Quantum Chromodynamics (QCD), the fundamental theory for strong interactions.

There are strong indications that the quark-gluon plasma is formed briefly in the course of heavy-ion reactions generating large energy density[15], but a clear proof is still lacking.

2 The description of primordial nuclear reactions occurring just after the big-bang showed (before the study of the Z_0 particles) that there are only three types of neutrinos[16].

3 Surprisingly enough, data about the natural reactor of Oklo (due to special conditions of uranium and water concentrations in the ground, a natural reactor started in Gabon about 1.7 billion years ago and worked regularly for one hundred thousand years) may shed some light on the famous problem of the variation of the physical constants, initiated by Dirac[17]. The latter suggested that fundamental constants (like $\hbar$, or c the velocity of light), may have vary during the eons. The concentration of some Samarium isotopes, which can be made by radiative neutron capture, seems to point to a slight decrease of the fine structure constant between the time of Oklo and the present time[18].

"Soddy, don't call it transmutation, or they will have our heads off as alchemists!"
(Ernest Rutherford)

References

[1] R. Lenoble, « Mersenne ou le mécanisme », Vrin, Paris, 1943
[2] E. Canseliet, « Alchimie », J.-J. Pauvert, Paris, 1964
[3] B. J. Becker, Science 301 (2003) 1232.
[4] A. Pais, « Inward Bound », Clarendon Press, Oxford, 1986
[5] J.-M. Gérard, Physicalia Magazine. Vol 28 n° 1 (2006) 27
[6] B. Russel, « Human Knowledge, Its Scope and Limits », Simon and Schuster, New York, 1948
[7] A. Einstein, Annalen der Physik, 17 (1905) 639
[8] J. Cockroft and E. Walton, Proc. Royal Soc. A 137 (1932) 229
[9] A. Einstein, « Atomic war or peace », The Atlantic monthly, Boston, Vol.180 N°5 (November 1945) 29
[10] J. Rotblat, « The early days of Pugwash » , Physics Today 54 (2001) 5
[11] A. Einstein, citation quoted by many citation listers. See G. Seldes,« Albert Einstein. the great citations » POCKET BOOKS, New York, A Division of Simon & Schuster, Inc.
[12] R. Clark, « *Einstein: The Life and Times* », World Publishing Company, New York, 1971.
[13] A. M. Hofmeister and R. E. Cross, Techtonophysics 395 (2005) 159
[14] W. Gudowski, Nucl. Phys. A654 (1999) 436c
[15] M. Nardi, Eur. Phys. J. C43 (2005) 85.
[16] Particle Data Group, “Review of particle physics”, J. Phys. G 33 (2006) 1
[17] P. A. M. Dirac, Nature, 139 (1937) 323
[18] S. Lamoreaux, Phys. Rev. D69 (2004) 121701