2.1 RADIOLOGY EDUCATION IN HUNGARIAN SCHOOLS

George Marx
Department of Atomic Physics, Eötvös University
Pazmany setany 1A, Budapest H-1117, fax 36-1-3722753

ABSTRACT

Basic concepts of nuclear physics are not more abstract and more difficult than those of electricity. For the orientation of the citizens of the 21st century, the Hungarian school curriculum has made them compulsory for all teenagers. According to the teachers' experience, the students find nuclear issues more relevant and more interesting than the topics inherited from the schoolbooks of earlier centuries.

1. AIM

School education -- relying on the pedagogical praxis of earlier teacher generations -- presents the mathematics of the Antiquity, the physics of the early Industrial Revolution (17/18th century) to the youth living in the 20/21st century. And the science teachers are surprised that the teenagers pay less and less attention to solve close-ended numerical problems about rigid bodies, direct currents, and geometrical optics, while living in an environment of semiconductor chips, mobile phones, and nuclear weapons. This conservative teaching habit excludes modern science and high tech from the human culture. Honest grassroots movements among the youth advocate a world free of 'alien' nuclear power and computer network, and advocate returning to the 'understandable' world of their ancestors.

The cleanest form of energy is offered by electricity, therefore it is the most comfortable and most popular option for people. In the last two decades Hungary utilized nuclear power to cover almost half of its electric consumption. This has made our country more independent from outside economical and political pressure. This is one of the main reasons, why statistical physics, atomic physics, nuclear physics, and astrophysics have become parts of the Hungarian high school curriculum. (The Japanese translations of the corresponding schoolbooks, written by Esther Toth, have been printed recently by the Maruzen Publishing Co. in Tokyo.) The actual official state curriculum has made the orientation in nuclear science compulsory already in the middle school, i.e. for all teenagers. Our experiences have been very positive: present teenagers -- even to-be poets, politicians, businessmen -- show much more interest towards radioactivity and nuclear power plants than towards forces acting on rigid bodies and direct current networks. Nuclear physics can be treated with much simpler mathematics than e.g. the resistance in case of alternating current.

2. NUCLEAR DROPLETS

Nuclei are much simpler structures than atoms, molecules, or solids. According to experiences (electric scattering on nuclei in the Rutherford experiment) nuclei are of *constant density*. Nuclei are made of (positive) *protons* and (neutral) *neutrons*. These constituents have almost equal masses. The protons repel each other electrically, but nuclei are still stable formations due to the intensive *nuclear attraction*, which acts among these nuclear particles. The nuclear attraction is about hundred times *stronger* than the electric repulsion, but it has a *short range*: much shorter than the size of the nucleus. These empirical properties of the nuclear force have the consequence that inside the nucleus each particle has the same number of neighbors, thus its binding energy is independent of the size of the nucleus, of the total number A of particles (constant heat of boiling). A particle on the surface, however, has fewer neighbors, thus its binding is weaker (surface tension). These characteristics of nuclear forces explain the constant density, the surface tension, and the spherical shape. Nuclei remind us on water droplets. The *fusion* of small droplets to a larger one would release energy, because fusion decreases the overall surface. But...

3. NUCLEAR VALLEY

Protons and neutrons -- like electrons in the atomic shell – are subject to the *Pauli principle*: on the energy ladder only two protons and two neutrons can stay on the same grade. This is why about half of particles are protons and half of them are neutrons in a stable nucleus. Thus the nuclear droplets are positively charged and repel each other by long-range electric force. The *intensity* of the short-ranged nuclear attraction and the *long range* of the electric repulsion make the nuclei to long-lasting structures. This explains the stability of chemical elements, which is the basic axiom of school chemistry.

The chemical properties of elements depend on their electron shells. The size of the electron shell depends upon the positive electric charge of the nucleus, i.e. on the number Z of protons in the nucleus. The Periodic Table of chemical elements terminates, however, at $Z<100$. The explanation is very simple: electric repulsion between two protons is about 100 times weaker than nuclear attraction. But the electric repulsion has a long range: the joint repulsion of all the other protons may become comparable to the nuclear attraction of the immediate neighbors in case of $Z \sim 100$, which destabilizes the very heavy (high Z) nuclei.

A nucleus is made of Z protons and N neutrons, altogether $A=Z+N$ particles. The average binding energy per particle is weakened if

a) A is small (large fraction of particles is on the surface),
b) Z is large (intensive electric repulsion acts among protons),
c) $Z>N$ (protons are forced to high energy levels by the Pauli principle,)
d) $N>Z$ (neutrons are forced to high energy levels by the Pauli principle).

Nuclear particles feel themselves most comfortable (possessing the deepest average binding energy per particle) at medium-sized nuclei ($A \sim 50$), with about 50 % protons and 50 % neutrons in them. This can be visualized by a map, indicating the *average binding energy per particle* versus Z and N. A narrow valley runs through the Z-- N} plane, more or less following the $Z=N$ line. Two sides of the valley ($Z>>N$ and $Z<<N$) are steep due to the Pauli principle. Starting from small $A=N+Z$ values, we walk downhill in the Nuclear Valley, due to the short range of nuclear attraction and decreasing relevance of surface energy; this is the *Yukawa slope*. For large Z values, however, we begin climbing uphill along Nuclear Valley, due to the electric repulsion between the many protons present in the nucleus, this is the *Coulomb slope*. At the deepest point we find the iron nucleus (A=56).

It is a remarkable fact of Nature, that the chemical elements populate the whole Nuclear Valley, but the most common metals are to be found at its deepest part: at the *Iron Sea*. We don't pick up a rusted iron nail, but we take a golden ring with.

	large Z Coulomb slope	
{$Z<<N$} Pauli slope	Z~N, A~50 **IRON SEA**	$Z>>N$ Pauli slope
	small A Yukawa slope	

4. RADIOACTIVITY

If one puts an arbitrary Z number of protons and N number of neutrons together, the system goes quickly to its energy ground state by emitting electromagnetic radiation within a tiny fraction of a second, in the same way as atoms do. But at nuclear transitions the emitted photons have much higher energy (*ã-radiation*).

If $N>>Z$, then the nucleus can transform itself to another nucleus of deeper energy by a *neutron proton* transmutation, releasing also a negative electron (and an antineutrino). But the transmutation of a nuclear particle is a *weak transition*, it takes much more time: minutes, days, even years. (*â-decay*).

If $Z>>N$, the *proton neutron* transmutation may lower the energy content of the nucleus. The proton can get rid of its positive charge by capturing an electron from the atomic shell. (By electron capture or by emitting a positive positron. In both cases a neutrino, too, is emitted. In order to decrease the lexical knowledge to be memorized by the students, we do not speak about positrons and neutrinos in the school. We speak only about electron emission to increase Z, electron capture do decrease Z. These â-transitions enable the nuclei to slide down the Pauli slope to reach the Nuclear Valley.) If we replace a neutron (standing high up on the energy ladder) by a proton, the new particle may find empty proton grades downstairs, therefore it jumps down, â-decays are usually followed by ã-decays.

If the electric charge of the nucleus is too large, by splitting into two parts it could decrease its energy: the two fragments would repel each other vehemently. But the first step of splitting would be the deformation of the spherical droplet, i.e. an increase of its surface, which means increasing surface energy. The energy will drop only after the formation of two spherical droplets out of a larger sphere: sliding down on the Coulomb slope may begin. Thus splitting of a large nucleus could liberate electric energy, but an energy barrier prevents it. A He nucleus may leak through this barrier by quantum tunneling, but that may take thousands, millions, even billions of years. (á-*decay*). For larger fragments the tunneling time would be even longer.

We experience that the nuclei, occurring in Nature, are to be found down, in the Nuclear Valley. This is the result of sliding down on the slopes. Radioactivity -- as *nuclear cooling* -- is a natural phenomenon in the same way as the cooling of hot water in a cup is -- but the released energies are larger, even million times larger.

5. OUR NUCLEAR HISTORY

In the Universe the most common chemical element is hydrogen, making about 75 % of the cosmic stuff. This hydrogen the leftover from the Early Hot Universe. In the first second of the cosmic history the temperature was so high, random thermal motion was so intensive, that composite nuclei could not survive. Cosmic history started with H. As if a shower had poured a lot of water at the Zero End of the Nuclear Valley. But positive protons repel each other therefore they cannot merge...

In the gradually cooling Universe gravitational attraction formed gas clouds. The work of gravity heated these contracting hydrogen clouds up to several million degrees. At such a high temperature there is a certain chance for the single-charged H nuclei (Z=1) to collide, to touch each other and to make He (Z=2) by nuclear fusion. The released nuclear energy feeds the starlight.

In the stellar interior the temperature is originally not high enough to make also the fusion of He nuclei (with charge +2e) possible. But when the H fuel of the star becomes exhausted, the gravitational pull heats the center to 100 million degree, and the fusion of He begins, three He make C, one more He makes O, these life essential elements. Such hot He burning stars are known as *red giants*.

When the He content of the star becomes exhausted, the star is very hot and it shines intensively. The energy loss is covered by further gravitational collapse. The central part of the star collapses to nuclear density, a *neutron star* is formed. The outer layers keep falling in and upon impact they are heated up to billion degree. At such a high temperature the collisions are so energetic, that nuclear droplets start boiling away. All nuclear reaction channels open up; the whole Periodic Table becomes populated. Nuclear matter is dispersed along the whole Nuclear Valley.

But this total nuclear freedom does not last long. Within minutes the heat of the layers falling in produces a thermal explosion: the giant star strips its outer layers off. Gas shells, rich in heavy metals, are ejected to the outer space. Faraway astronomers can register the brilliance of the quickly expanding hot gas sphere as *supernova explosion*. In the heat of this explosion even the heaviest elements (Z>90) were formed. Such an explosion occurred in this region of the Galaxy 4.6 billion years ago. (Its time can be read from radioactive clocks: by measuring the ratio of radioactive elements and their decay products in the most ancient meteorites.)

From the collision of the ejected dirty supernova-material and the pure interstellar hydrogen gas the Solar System has been formed. Thus the Sun is made of the lightest elements, with some metallic concentration. As the work of gravitational attraction warmed the Sun above 10 million centigrade, the nuclear fusion H Sunshine is fed by the liberated binding energy of helium nuclei. (*Helios* is the Greek name of the Sun.)

The innermost planets were formed from dust grains, covered by the ice of H_2O and CO_2. The sunshine made these planet lukewarm, thus the volatile H_2, He, CH_4, Ne escaped. The radioactive elements, inherited from the supernova, melted the Earth in the first half billion years of her existence. Heavy metals (Fe, Co, Ni) sunk to the core of the planet. Lighter metallic oxides and silicates made the crust. As the radioactivity decreased, the crust solidified. Volcanism released CO_2 and H_2O, to make atmosphere and ocean. The sunshine, produced by *nuclear fusion* in the Sun, keeps the oceans liquid, warms the atmosphere, drives the winds and rivers, and feeds life by photosynthesis. Geothermal heat, produced by *radioactive nuclei* inside the Earth, manifests itself in hot springs and volcanism. These two phenomena, *the two flows in the Nuclear Valley towards the Iron Sea*, keep the Universe changing and they shape the face of our home planet.

Deeply inside the Earth the melted rock material expands, becomes lighter, and rises to the surface. Here the magma cools, solidifies, shrinks, becomes heavier and sinks down. This geothermal circulation drives the plate tectonic motion: continents collide, mountain chains are formed, between the continents oceanic rifts open up. India hits Asia at a speed of 4 cm/year, producing the Himalayas. Such plate tectonic drift has made the chain of islands, which is Japan today.

The composition of the Sun is changing due to nuclear fusion. Its temperature rises slowly; its luminosity increases by 5 % per billion years. The water was liquid on Venus 3-4 billion years ago, and then it evaporated to the atmosphere. The icy moons of the Jupiter will melt in 2-3 billion years from now. But liquid ocean is present on the Earth since 4 billion years, offering time long enough for biological evolution. What sort of air conditioning preserves the steady temperature of our blue-green planet?

The sunshine warms the soil. The lukewarm soil emits infrared radiation. Terrestrial temperature depends on the balance of heat input and output. The actual temperature depends sensitively on the CO_2 concentration of the atmosphere, because CO_2 molecules absorb this infrared radiation. Without the atmospheric CO_2 the Earth would be as frozen as the Moon is.

CO_2 is released by volcanism and is dissolved in rainwater, to make carbonic acid: CO_2+H_2O H_2CO_3. Carbonic acid attacks volcanic silicates and dissolves them into seawater in the form of limestone: $CaSiO_3 + H_2CO_3$ $CaCO_3 + H_2O + SiO_2$. The sedimentary limestone and sand sinks deeper and deeper. Down the limestone dissociates due to geothermal heat: $CaCO_3$ $CaO+CO_2$. The CO_2 rises into the atmosphere in carbonated springs. The calcium oxide and sand make $CaSiO_3$ again, and the molten silicate -- due to thermal expansion -- flows to the surface at volcanic eruption. This steady circulation of CO_2 is driven by the weathering of rocks (sunshine) downwards and volcanism (radioactivity) upwards.

If the climate warms up, e.g. due to increased solar luminosity or to increased CO_2 concentration in the atmosphere, the stronger thermal motion accelerates the chemical reactions. Faster weathering means extraction of more CO_2 from the atmosphere, thinning greenhouse, and lower temperature. (The speed of the geochemical reactions in the deep is not influenced by temperature changes outside) If the climate cools, weathering slows down, less CO_2 is extracted, and the increasing atmospheric CO_2 warms up the atmosphere. This *negative feedback* keeps the temperature of the biosphere at constant level. Our special planetary air conditioning is driven by sunshine (nuclear fusion) and geothermal heat (nuclear radioactivity). This air conditioning does not work on Venus (the planet is too hot, it does not have rainwater to make carbonic acid). It does not work on Mars either (the planet is too small, it cannot preserve radioactive heat to drive plate tectonics and volcanism). On the Earth, we are fortunate. The only problem is that the reaction time of the terrestrial air conditioning -- offered by Nature -- is rather long, several thousand years. It cannot offer defense against such a sudden attack like converting all fossil fuels into CO_2 during the few hundred years of the Industrial Revolution.

Thermonuclear fusion in the Sun and natural radioactivity in the Earth are both delayed cooling of supernova materials. They are natural phenomena, as the cooling of hot water in the pot and flow of rivers into the ocean. Well, the phenomena of Nature can be controlled and utilized, as the water mill does with the energy of the rainwater running down the valley. The efficiency can be enhanced; the level difference can be increased by constructing dam. Why don't we utilize the natural flow of nuclear matter along the Nuclear Valley towards the Iron Sea? The discovery of *nuclear fission* made the artificial transmutation of very heavy uranium into medium-heavy nuclei possible in nuclear reactors. A nuclear power plant is a straightforward utilization of a natural phenomenon in the same way as the water mill or windmill is. The advantage of nuclear power plant with respect to chemical power plants is that it does not affect the carbon-dioxide greenhouse.

It is a psychological fact, however, that nuclear power was discovered in the 20^{th} century, in our lifetime. Humans have not got used to it through generation, like they learned to use firewood or riverflow or coal. It is now the duty of radiology education, to express in simple terms, what nuclear energy is. In conclusion, let us quote James Lovelock, the British atmospheric chemist, who has elaborated the Gaia model of the terrestrial biosphere, which has become the guiding principle of environmentalists:

-- The natural energy of Universe is nuclear energy, this feeds the starlight on the sky. From the point of view of the Director of the Universe chemical energy, wind energy, and water mill are insignificant phenomena, as a coal fired star would be. And if it is so, if the Universe of God is driven by nuclear power even today, then why do people demonstrate against making electricity out of nuclear power?

APPENDIX

For those teachers, who like formulas: The volume of the spherical nucleus is proportional to the number A of its constituents, thus its radius is $R=R_0A^{1/3}$ ($R_0=1.2\cdot10^{-15}$m). The binding energy contains the main (negative) term proportional to A. The binding is decreased by the (positive) surface energy proportional to 4ð R^2 and by the Coulomb energy $0.6(Ze)^2/4$ðå$_0R$. Due to the Pauli principle, a positive n^2 term appears in E/A (binding energy per particle) if the relative neutron excess $n=(N-Z)/A$ is different from zero. These altogether give the following formula:

$$E(A,Z)/A=-\mathring{a}_B+\mathring{a}_S A^{-1/3}+\mathring{a}_C Z^2/A^{4/3}+\mathring{a}_P(A-2Z)^2/A^2.$$

This is the equation for the Nuclear Valley, the positive terms describe the Yukawa slope (decreasing with increasing A), the Coulomb slope (rising with increasing Z) and the Pauli slopes (rising with increasing n^2). Comparison with the measured binding energies gives: $\mathring{a}_B$=2.52pJ, $\mathring{a}_S$=2.85pJ, $\mathring{a}_C$=0.11pJ, $\mathring{a}_P$=3.80pJ. For a fixed A particle number, E is a quadratic function of Z, its minimum Z_{min}}$=0.5A/(1+0.0075A^{2/3})$ gives the most favorable proton content of the nucleus.