NUCLEAR PROCESSES IN NATURE

Zsolt Fülöp and **Zoltán Elekes**
ATOMKI (Institute for Nuclear Research), Debrecen, Hungary

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Summary

Nuclear processes govern a wide range of phenomena in nature. Some interesting cases are discussed here giving a special attention to heavy element nucleosynthesis and the nuclear reactions behind.

1. Introduction

The understanding of our cosmic heritage combines several fields involving astrophysics, geophysics and nuclear physics. Nuclear reactions are at the heart of these fields: they influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation, neutrino luminosity, and evolution of stars. A good knowledge of nuclear reactions is essential to understanding this broad picture.

A nuclear process can be induced (e.g. chain reaction) or occur spontaneously (e.g. radioactive decay). One can observe the result of a nuclear process via the detection of the emitted particles or the energy released. Because of the different nature of emitted particles the observation of nuclear processes demands a wide range of techniques depending on the properties of the given reaction. Earth (Section 2) as well as celestial objects (Section 3) can be considered as sources of radiations and places where nuclear reactions occur. Nevertheless, once the nature of a given nuclear reaction is understood it can be used as a tool for further investigations as it is described in Section 2.1 where the Earth as the source of neutrinos is discussed.

A unique possibility is provided when a given nuclear reaction creates a radionuclide with a finite half-life. Depending on the half-life one can use those nuclides as chronometers on different time scales. This, in combination with sophisticated ultra sensitive nuclear detection methods allows tracing back a possible supernova explosion that might have been occurred near Earth (Section 3.2.). Similar studies on the high-precision determination of isotope abundances revealed that a natural nuclear reactor existed in Africa about 1.8 billion years ago (Oklo phenomenon, Section 2.2).

A special section is devoted in this chapter to the synthesis of heavy elements via neutron capture reactions (s- and r-processes). The astrophysical p-process is presented in detail as an example to show the complexity of theoretical and experimental investigations aiming to understand the abundances of a special group of stable isotopes. Here, in addition to the relevant nuclear reactions, auxiliary, e.g. inverse reactions should be studied too to provide all the details of the scenario. Those studies aiming at nuclear reactions that occur far from the valley of nuclear stability called for special devices that can provide short lived nuclei energetic enough.

As a direct link between natural radioactivity and life, Section 2.3, introduces microbes that need radioactivity to survive.

The subjects listed above are far from being complete. The aim of the present work is to provide examples from very different fields to prove the crucial importance of nuclear processes in nature. Note that naturally occurring decay series are discussed elsewhere in the Encyclopedias. (See: *Radiochemistry and Nuclear Chemistry*.)

2. Terrestrial Nuclear Processes

2.1. Geoneutrinos

We live in neutrino showers; billions of them are passing through our body in every second. They interact with matter very rarely and come from cosmic objects like stars and supernovae but Earth itself is also a rich source of this interesting particle. During the decay of the natural, terrestrial radioactive materials (uranium, thorium and potassium), mainly anti-neutrinos are emitted in a chain of reactions written in a compact form here:

$$\begin{aligned}
&{}^{238}\mathrm{U} \xrightarrow[100\,\%]{} {}^{206}\mathrm{Pb} + 8\ {}^{4}\mathrm{He} + 6\ \mathrm{e}^{-} + 6\,\overline{\nu}_{\mathrm{e}} + 51.7\ \mathrm{MeV} \\
&{}^{232}\mathrm{Th} \xrightarrow[100\,\%]{} {}^{208}\mathrm{Pb} + 6\ {}^{4}\mathrm{He} + 4\ \mathrm{e}^{-} + 4\,\overline{\nu}_{\mathrm{e}} + 42.7\ \mathrm{MeV} \\
&{}^{40}\mathrm{K} \xrightarrow[89.28\,\%]{} {}^{40}\mathrm{Ca} + \mathrm{e}^{-} + \overline{\nu}_{\mathrm{e}} + 1.311\ \mathrm{MeV} \\
&{}^{40}\mathrm{K} + \mathrm{e}^{-} \xrightarrow[10.72\,\%]{} {}^{40}\mathrm{Ar} + +\nu_{\mathrm{e}} + 1.505\ \mathrm{MeV}
\end{aligned} \tag{1}$$

Nowadays, these are popularly called *geoneutrinos*.

Directly, very little is known about the interior of our planet. The deepest hole which was ever drilled goes only 12 km below the surface so geochemical analyses can produce results only for this region. From seismic studies, the density profile of the whole Earth can be mapped, however this does not tell anything about the composition. Presently, scientists think that Earth's structure is layered and can be divided into 3 regions: crust, mantle and core. The crust consisting of light elements like potassium, sodium, silicon, calcium and aluminum silicates is sometimes subdivided into a thicker continental and a thinner oceanic part. Earth's mantle with about 3000 km depth gives 68% of the total mass of our planet. It mainly contains magnesium and iron silicates. This can also be divided into subgroups such as lower and upper mantle. The main questions about the mantle are whether it moves as a single object or layer-by-layer and whether it is homogeneous or not. The core is believed to be made of iron and some other elements like nickel in small concentrations. The distribution of radioactive elements is expected to be heterogeneous: the largest amount of uranium, thorium and potassium is thought to be in the crust. The concentration of these elements in the mantle is smaller; however, their amount is comparable to that of the crust because of the large mass difference between these layers. Most of the researchers think that the radioactive contribution of the core is negligible but it is noted that a number of people suggested that some potassium might be hidden at the center of the Earth. So, we construct models (for geoneutrino studies a crust+mantle system) which might explain the observables we can detect such as heat dissipation on the surface. It is believed that radiogenic heat is a major contribution to the total geothermal heat. Because the geoneutrino flux and the radioactive heat flux have been shown to be tightly correlated, the measurement of geoneutrinos plays crucial role in confirming the planet models and the structure of Earth. Depending on the models, the total power output at the surface ranges from 30 to 44 TW. The so-called Urey ratio measures the amount of heat power of radioactive origin to the total output. Most of the models expect this ratio to be around 0.5, so the remaining heat must come from other potential contributors, such as core segregation, inner-core crystallization, accretion energy or extinct radionuclides. However, there are alternatives which suggest the Earth's heat to be fully radiogenic with an Urey ratio of 1. Since the consecutive beta-decays ending in stable nuclides (1) are very well known, the neutrino energy distributions are also well established. Because the absorption of neutrinos traveling through the rocks can be neglected, based on the energy distributions, the expected flux can be derived at the surface as well. There is a contribution to this picture by the phenomenon of neutrino oscillations, i.e., different neutrino flavors like electron, muon and tau neutrinos can transform into each other becoming undetectable by instruments sensitive only to a special flavor.

Recently, a major advance took place in neutrino geophysics by the KamLAND collaboration which actually played a crucial role in the neutrino oscillation experiments together with Sudbury Neutrino Observatory (SNO) in Canada and provided evidence that neutrinos are not massless particles. KamLAND stands for Kamioka liquid scintillator antineutrino detector and is situated in the Kamioka mine 1000 m underground in Japan. In this experiment, the electron antineutrinos can be detected in about 1 kton of liquid scintillator through the neutron inverse beta-decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n\,, \qquad (2)$$

where anti-neutrinos interact with protons forming neutrons and positrons. The scintillation light from the positrons gives the prompt event. The neutrino energy is correlated with the positron energy:

$$E_\nu \approx E_{e^+} + 0.8\ \text{MeV}\,. \qquad (3)$$

A little later (after about 200 μs), neutrons are captured by protons producing deuterons and gamma-rays of 2.2 MeV energy the scintillation light of which is called the delayed event. With coincidence technique, the background can be reduced significantly in this way.

The results are shown in Figure 1 as the energy distribution of the 152 possible antineutrino events. The expected geoneutrino signals are plotted as dot-dashed red line for ^{238}U and dotted green line for ^{232}Th. The other colored lines represent background contributions, while the total background is shown as thick black line. Thus, 20-25 events were considered to be due to true geoneutrinos. This is a pioneering work and the interpretation of the results is not straightforward. Its strength lies in the fact that it has been demonstrated that geoneutrinos exist at observable level. And what is more, the data suggest that the upper limit of radiogenic heat from uranium and thorium is 60 TW with a central value of 16 TW which is consistent with most of the available models. It is worth noting, however, that the high background in the spectra can be reduced since most of it originates from nearby nuclear reactors and contamination in the detector material itself. Also, the sensitivity of the detection might be increased by pushing the threshold of the system lower in order to accept signals from potassium events.

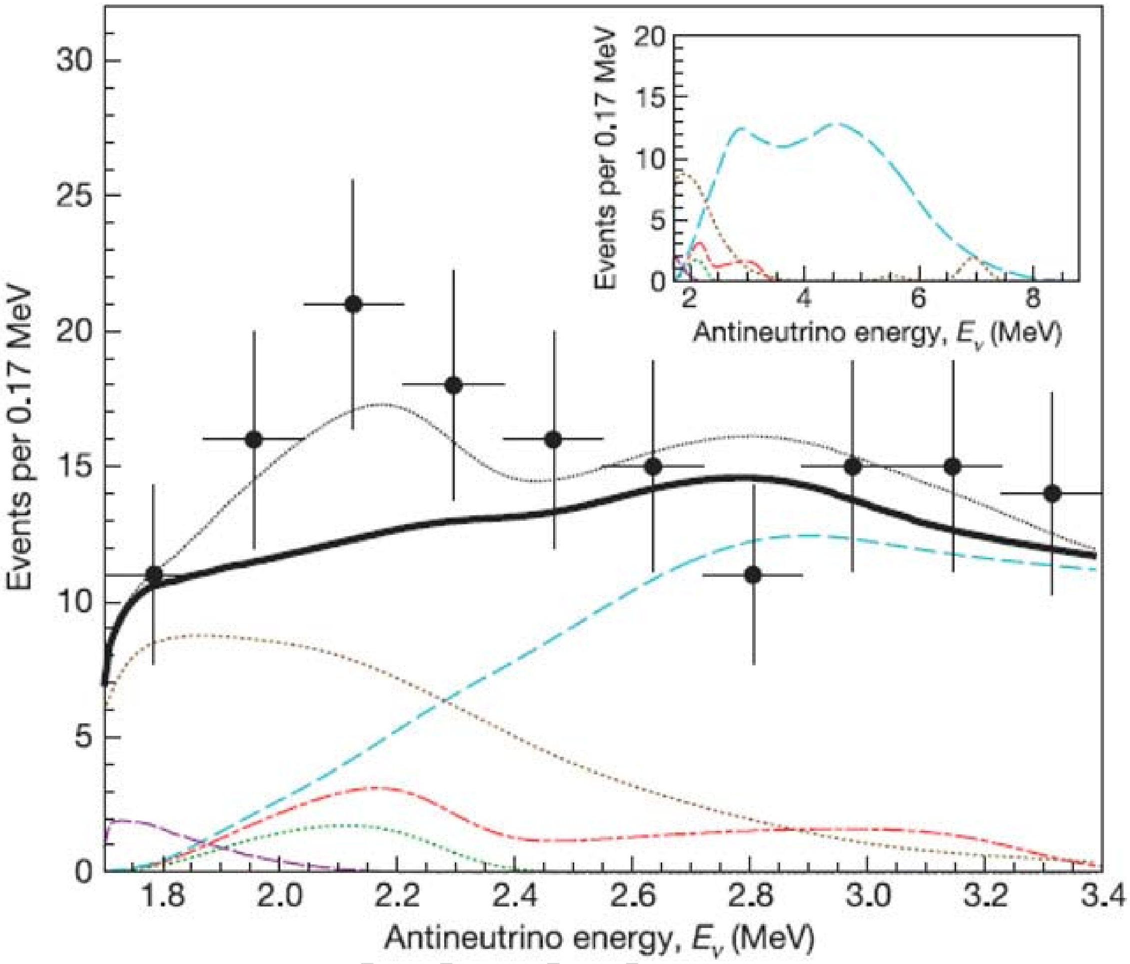

Figure 1. Energy distribution of antineutrinos detected by KamLAND
[taken from T. Araki et al., *Nature*, **436** (2005) 499.]

2.2. The Oklo Phenomenon

Sometimes nature brings our strangest dreams to fruition. In 1956, Paul Kuroda described the conditions under which a natural nuclear reactor could exist:

- this must have happened billions of years ago when the ^{235}U abundance was higher than today,
- the concentration of uranium in the carrying ore must have reached a level of 70%,
- the dimension of the reactor should be critical not to let neutrons escape, and
- the ore must be porous in order to keep some water inside for moderating the neutrons.

In 1972, French scientists discovered anomalous abundance of ^{235}U in Oklo, Gabon during their routine analysis of uranium ores. The abundance of ^{235}U is 0.720% presently and is well-known from measurements. What the initial suspicion of the analytical laboratory caused was a 0.717% concentration of ^{235}U. Later on several other samples were investigated and even larger concentration differences were found like 0.44%. There were many attempts to explain this phenomenon including even UFOs and an old, advanced civilization but quite soon researchers agreed that Kuroda's dream came true and an ancient natural reactor was found in Africa. Later on, several reactors were unearthed although most of them are mined today; however OKLO15 is preserved and open for public visitors.

The conditions at the site completely fulfilled the requirements drawn theoretically. Since the decay rate of ^{235}U and that of the most abundant uranium isotope $^{238}\mathrm{U}$ are different, $^{235}\mathrm{U}$, the fuel of nuclear fission reactors, represented a larger fraction (~3%) of uranium about 2 billion years ago. This is enough to maintain self-sustaining chain reaction when the other conditions are met. It is worth noting that a nuclear reactor can be based on today's natural uranium but it needs a special design and deuterated water as a moderator. These reactors are called CANDU – CANada Deuterium Uranium.

Presumably, the uranium content was driven to the surface by volcanic activity and dissolved from the volcanic rock by water. Since the oxygen content of the atmosphere became higher long time ago on a geological scale due to photosynthesis turning the reducing atmosphere into an oxidizing one, uranium could oxidize. Because uranium-oxide is insoluble in water it could be depleted in high concentration. The Oklo reactors probably worked in a cyclic way with timing similar to a geyser. Meshik and his colleagues collected samples consisting of grains of uranium oxide surrounded by aluminum phosphate. The phosphate crystals confined inert xenon gas which could be produced only by nuclear processes. During the fission, uranium was split into lighter elements which decayed into, among others, xenon. The investigations showed that the measured concentrations of the xenon isotopes are odd in that they differ from the distribution observable in a normal, continuous-working reactor and the results could be explained by assuming a pulsing phenomenon. Therefore, the scientists came to the conclusion that about 1.7 billion years ago, the reactors became critical and worked for about 150 000 years. During the operation heat was produced so the surrounding water boiled. Thus, the reactors went to subcritical phase after which water could penetrate the ores again switching on the nuclear reactions. Finally, the $^{235}\mathrm{U}$ fuel was exhausted so the reactors shut down forever.

The Oklo phenomenon is important not only because of its uniqueness and the miracle that it did not blow off and a controlled fission could take place but also due to its consequences. Oklo can be regarded as an experimental place for radioactive waste disposal and storage. Exhaustive studies showed that most of the fission products remained at the site and only a small fraction of the waste was transported to a limited distance of some meters. This is quite good and reassuring news since it is difficult to imagine worse conditions to store nuclear by-products than the environment in Oklo where the radiating material was without any containers exposed to groundwater flows.

Another significant consequence of the phenomenon was first realized by Shlyakhter who suggested a measurement that could give a limit on the change of the fine-structure constant α. This key quantity, which was measured later, is the abundance ratio of $[^{149}\mathrm{Sm}]/[^{147}\mathrm{Sm}]$. Since these isotopes are not fission products their ratio could change by neutron capture reactions on $^{149}\mathrm{Sm}$ converted to $^{150}\mathrm{Sm}$ decreasing its amount.

Shlyakhter showed that the cross section of this reaction depends on a capture resonance of neutron of about 0.1 eV of energy. This resonance is a consequence of an almost complete cancellation of the electromagnetic and the strong force. Measuring the capture cross section at the time of the reaction, a constraint can be given on the resonance energy which can be further related to a constraint on the time variation of the fine-structure constant. So far, many results were published which are ambiguous. Sometimes authors give only upper limits but the analyses giving definite effect contradict to each other even in the sign of the change, so we cannot say whether the fine structure constant increased or decreased. The major problem is that we have to know the neutron spectra quite well in order to calculate the cross section of the capture reaction with acceptable uncertainty. These spectra are model-dependent therefore realistic reactor models are needed to get reliable constraints on the change of α. On the whole, it seems that a bound can be given from Oklo samples which is consistent with α being a constant, but also allows small changes over time.

There is also a cosmological method to measure the possible change of the fine structure constant although it is less sensitive but covers a wider time range. The light from distant quasars represents the status of the Universe in the past. It travels through enormous distance until it arrives at Earth. During its journey it scatters on the interstellar gas which puts its fingerprint on it by absorption lines which are redshifted due to the expansion of the Universe. The variation in α makes changes in the energy levels of the gas atoms and therefore, in principle, a shift is observable in the absorption lines if α was different billions of years ago, the time needed for the light to reach our planet. Results are again controversial and the evidence for any variation of α looks very weak.

2.3. Living on Radioactivity

It is getting more and more well-known and almost a banal phrase that radioactivity is a natural part of our life and its consequences are all around us. However, nuclear processes sometimes show their importance in strange ways that we would have never imagined.

The origin and limits of life on Earth are still open questions for scientists. For example, deep ocean was *Terra Incognita* for a long time and researchers are just at the dawn of a new era of searching for life under extreme conditions. Extremophiles are tiny microorganisms which can live under circumstances that other living things could not tolerate like extreme heat, cold, dehydration, acidity and so on. The amazing phenomenon is that they do not just survive these conditions but grow, reproduce and simply enjoy these kinds of environment. Organisms, which can enter a kind of freeze-dried state, have been found, for example, in Atacama Desert. When water is not available they just suspend their life functions but if some water appears they revive. Other microbes have such cellular ingredients that prevent ice crystal formation so they can live in extra cold environments. Deep under the ocean surface, sometimes giant cracks are formed on the crust of our Earth and extremely hot mineral water is ejected. Even in this hostile land living beings can exist. These creatures developed an alternative to photosynthesis: chemosynsthesis converting hydrogen sulfide into food.

Acidophiles and alkalophiles are such organisms which can thrive under acidic or alkaline conditions. In Yellowstone Park, microbes, which adapted to a pH value as low as 0.5, were found, while microbial species live in soda lakes with pH value of 10 in Africa. Furthermore, Conan the Bacterium (*Deinococcus radiodurans*) can withstand extreme radiation thousand times more than any other life form on Earth.

Recently, Li-Hung et al. found strange bacteria in the 3 km-deep Mponeng gold mine, South Africa in groundwater surrounded by 2.7 million-year-old rock formation. The age analysis of the water in which they live showed that they were separated from the surface very long time ago and it was also proved that the hydrocarbons found around them did not come from other living sources. It is difficult to determine how long these creatures were cut off from sunlight but researchers think it is somewhere between 3 and 25 Ma.

On Earth, microorganisms can gain energy by coupling the oxidation of hydrogen to the reduction of compounds such as oxygen, nitrate, Fe(III), sulfate or carbon dioxide. Molecular oxygen, which is required for the production of significant quantities of nitrate, Fe(III) and sulfate, is available above ground because of photosynthesis. Li-Hung's microbes are different. As a matter of fact, they live on radioactivity. The rock contains radioactive uranium, thorium and potassium as well as a common mineral, pyrite. A cascade of reactions occurs feeding the microbes with energy. First, radioactivity decomposes water molecules (H_2O) into their components: hydrogen (H_2) and oxygen (O). The detached oxygen atoms combine with adjacent water molecules to make hydrogen peroxide (H_2O_2). The peroxide then reacts with pyrite (FeS_2), producing sulfate ions (SO_4^{2-}) that the microbes consume.

The scientists think that these organisms, probably, are not so different now than when they got underground since they grow very slowly in order to conserve the scarce nutrients. Unlike their above-ground relatives, which divide about every day, they reproduce once a year at most. Their environment is very similar to that of the early Earth, they cannot even stand oxygen. Thus, the existence of these microbes puts a question whether the life on Earth began underground and might also change the way of searching for life on other planets like Mars.

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Biographical Sketches

Zsolt Fülöp was born in 1964, Debrecen, Hungary. He is a scientific advisor in ATOMKI (the Institute of Nuclear Research of the Hungarian Academy of Sciences), Debrecen, Hungary. He received his Ph.D. degree in nuclear physics in 1992 based on his work in nuclear structure studies. As a postdoctoral fellow of ATOMKI he started to explore the nuclear physics aspects of nucleosynthesis and earned the D.Sc. degree of the Hungarian Academy in 2006. His interest is ranging from underground nuclear physics through ultra low energy collisions and the astrophysical p-process to exotic nuclear physics. He is individual member of the European Physical Society and ordinary member of the Nuclear Physics Board of the European Physical Society. He organized the first (2002) and second (2005) conferences of the series entitled '*Nuclear Physics in Astrophysics*'. As a coauthor of more than 200 papers published in scientific journals he has been awarded the Selenyi Prize of Hungarian Physical Society and the Prize of the Section of Physical Sciences, Hungarian Academy.

Zoltán Elekes was born on January 12, 1974 in Budapest, Hungary. He spent his university years at the Kossuth Lajos University, Hungary and got his master degree as a physicist in 1997 there. He obtained his PhD in 2001 at the University of Debrecen, Hungary for ion beam related applied atomic and nuclear physics studies. Besides, during his PhD work, he also carried out simulations of radioactive material in groundwater in the framework of EU PHARE program together with English colleagues in Harwell Laboratory. After the PhD, his interest turned back to fundamental nuclear physics, therefore he moved to the Physical and Chemical Research Institute (RIKEN), Japan in 2002. During his two-year-stay he used radioactive ion beams to study extreme atomic nuclei far away from the valley of beta stability. He had a leading role in these experiments and in the discovery of exotic phenomenon of decoupling of valence nucleons from the nucleus core. He also made essential contribution to the clarification of the changing of magic numbers in neutron-rich nuclei. After his return to Hungary in 2004, he has been working for the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI). He was given habilitation at ATOMKI in 2005. He has joined the Nuclear Astrophysics Group of ATOMKI as a senior research fellow and has been carrying out nuclear physics experiments in this field and has been continuing his basic research in Japan, as well. He is the author of about 80 scientific papers and has given about 60 contributions to conferences.