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# FINAL REPORT ON THE

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## *The study of Earth heat dissipation and its uncertainties*


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## Abstract

Neutrino geophysics, the study of the Earth's interior by measuring the fluxes of geologically produced neutrino at its surface, is a new interdisciplinary field of science, rapidly developing cooperation between geology, geophysics and particle physics. Geoneutrinos, antineutrinos from long-lived natural isotopes responsible for the radiogenic heat flux, provide valuable information for the chemical composition models of the Earth.

In this work the decay chains of the most common radioactive elements in the Earth's crust are investigated. The total energy release in each of the chains is calculated taking into account the decay probabilities and their uncertainties. The purpose of this work is the evaluation of contribution of long-lived radioactive elements to the heat generation of the Earth. In this work we used one of the Bulk Silicate Earth (BSE) models to predict the chemical composition and therefore to estimate the Earth's heat release. The uncertainties of results are evaluated for the first time.

# Contents



## 1. Introduction

The heat flux on the surface of the Earth is partially provided by the energy released in the radioactive decay of long-lived isotopes, which are naturally present in its crust and mantle. Geoneutrinos, antineutrinos emitted in these decays can provide useful geological information when detected. But neutrinos are difficult to detect, since they almost do not interact with matter. It is expected that measurements of neutrinos exact interaction speeds will shed light on the abundance and distribution of radioactive elements inside the Earth beyond the direct measurement. The natural radioactivity of the Earth is a powerful source of heat and knowledge of radioactive contents in the bowels of the Earth is important for solving many geoscience problems.

The importance of radioactivity in the heat balance of the Earth was understood quite early after its discovery. Calculations showed that the distribution of radioactive elements is not uniform over the entire volume of the Earth, since the concentration of radioactive elements in the crust extrapolated to the entire volume will lead to a significant increase in heat generation than the known total heat flux from the Earth. In other words, these calculations showed that the concentration of radioactive elements in the mantle and core is lower than in the crust [1]. In the 1970s, uranium and thorium concentrations were measured in samples of mantle rocks extracted from the ocean floor, and they turned out to be low. Consequently, natural radioactive isotopes are concentrated mainly in the continental crust. The energy from the decay of radioactive isotopes is an important source of heat on

Earth, which is estimated at about half the total heat generated by the Earth. The Earth radiated more radiogenic heat at the initial stage of its existence than it does now, primarily because at that time there were more radioactive elements in the rocks. The decay of the $^{26}$Al isotope with a life span of 0.717 million years was the main source of heat on the early Earth.

There are various types of radioactive decays among the radioactive isotopes that heat the Earth. The energy of α-decays is completely converted into heat, and the energy released in β decays is partially absorbed by the antineutrino. Historically, the β-decay study provided the first physical evidence for the existence of neutrinos. The continuous β-decay spectrum was a mystery, since there was no visible third particle providing a balance of energy and angular momentum. Pauli suggested the existence of a light-neutral particle, which he called the neutron. This “neutron” emitted during β-decay will explain the lack of energy and angular momentum. In 1931, Enrico Fermi renamed the neutrino particle, which literally means "a neutral one." The interaction of neutrinos with matter is extremely weak, and its detection was an experimental problem during a quarter of a century, conducted only in 1956 using the experiment of Raines and Cowan [2]. Since each β-decay is accompanied by an antineutrino emission, the detection of these antineutrinos will mean the registration of the corresponding β-decays in the inner part of the Earth.

The energy released in radioactive decays is strictly connected to the amount of antineutrinos produced in these decays. The total neutrino production rate (or luminosity) $L_\nu$ can be related to the mass of radioactive isotopes contained in the Earth using the data from Table 1:

$$L_\nu = [(7.64 \pm 0.1) \cdot M(U) + (1.63 \pm 0.1) \cdot M(Th) + (2.765 \pm 0.007) \cdot 10^{-3} \cdot M(K) + \ldots] \cdot 10^{24}\ s^{-1}$$

A similar relation between radiogenic heat production $H_R$ and the mass of radioactive isotopes can be expressed as:

$$H_R = [(9.849 \pm 0.013) \cdot M(U) + (2.64 \pm 0.02) \cdot M(Th) + (3.358 \pm 0.008) \cdot 10^{-3} \cdot M(K) + \ldots] \cdot TW,$$

where masses of corresponding elements are in units of $10^{17}$ kg, and 1 TW is $10^{12}$ W. The antineutrino luminosity and heat production of other elements from the list of long-lived isotopes have been calculated in [3], all the contributions are at least order of magnitude lower than above-mentioned. So, the purpose of this work is to calculate the coefficients presented in the above formulas.

Geoneutrino flux measurements will provide answers to the still controversial questions about the natural radioactivity of our planet: what is the radiogenic contribution to the total heat generated by the Earth? How much uranium, thorium and potassium are distributed in the crust and mantle? What are the mass ratios of the planetary Th / U and K / U? How are uranium and thorium distributed in the crust and mantle? Is the mantle chemically homogeneous, multi-layered or more complex? Are there mantle tanks enriched with U and Th? Are geochemical models of Bulk Silicate Earth (BSE) consistent with geoneutrino data? And which of the proposed models of the Earth will correspond to the observed flux of geoneutrinos [4]?

## 2. Geoneutrino origin and the Earth heat

The natural radioactivity of the Earth is associated with the presence of long-lived radioactive isotopes (radionuclides) with a half-life of the order of billions years, which is comparable with the age of the Earth and the Solar System. The complete list of these isotopes (including α- and β-radioactive nuclides) contains 29 nuclides, another six nuclides have the half-life of more than 80 million years. Despite the fact that this is a significant period of time these isotopes survived in appreciable quantities till nowadays. These 35 natural radioactive nuclides consist of primordial nuclides with different abundances and lifetimes, but the main contribution to the Earth's radioactivity is provided only by few of them, namely isotopes from decay

chains, starting with $^{238}$U and $^{232}$Th, and also from $^{40}$K decays, with some contribution from the $^{235}$U chain and from $^{87}$ Rb and $^{147}$Sm decays.

Electronic antineutrinos ($\nu_e^-$) appear in radioactive β-decay:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}_e,$$

where A and Z are mass and atomic number of the parent nucleus. The daughter nucleus Y has the same mass number A as the nucleus X. The mass difference $Q_0$ between the parent and daughter nuclei is distributed between the electron and the antineutrino, providing continuous energy of the electron spectrum (and, hance, of the corresponding neutrino). Due to the tiny cross section of interaction with matter, neutrino carries away a significant fraction of the total energy release. The energy of electrons emitted during β-decay is converted into heat, called radiogenic. In accordance with modern understanding, radioactive decays are sources of about half of the total heat flux of the Earth, the second half of the heat associated with the secular cooling of the Earth.

## 3. Long-lived radiogenic elements

Let's start with a review of radiogenic elements. The most important decays from the geophysical point of view are in the chains of decays of U and Th:

$$^{238}_{92}U \rightarrow {}^{206}_{82}Pb + 6e^- + 6\bar{\nu}_e + 51.77\ \text{MeV},$$

$$^{235}_{92}U \rightarrow {}^{207}_{82}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.40\ \text{MeV},$$

$$^{232}_{90}Th \rightarrow {}^{208}_{82}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.66\ \text{MeV},$$

and in two channels of $^{40}$K decay (β-decay and electron capture):

$$^{40}_{19}K \rightarrow {}^{40}_{20}Ca + e^- + \bar{\nu}_e + 1.311\ \text{MeV},$$

$$^{40}_{19}K + e^- \rightarrow {}^{40}_{18}Ar + \bar{\nu}_e + 1.505\ \text{MeV}.$$

Two more decays of definite significance for geophysics are the decays of $^{87}$Rb and $^{147}$Sm. Rubidium is the 23rd most common element in nature, so that despite its

relatively low specific heat release, its contribution may be important in accurate calculations:

$$^{87}_{37}\mathrm{Rb} \rightarrow {}^{87}_{38}\mathrm{Sr} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}} + 0.2833\ \mathrm{MeV}.$$

Samarium is only on the 40th place among the most common elements. The isotopic abundance of radioactive $^{147}$Sm is lower than that of $^{87}$Rb, but its α-decay is more energic, $E_0$ = 2.3 MeV. As result it contributes more to the total than $^{87}$Rb.

The main characteristics of the three decay chains and three isotopes, which provide a main contribution to the radiogenic heat of the Earth, along with the characteristics of the accompanying neutrinos/antineutrinos are listed in Table 1. The details of the calculations are given in Tables 2–4. The main decay chains are shown schematically in Fig.1-3.

| | **$^{238}$U** | **$^{235}$U** | **$^{232}$Th** | **$^{40}$K** | **$^{87}$Rb** | **$^{147}$Sm** |
|---|---|---|---|---|---|---|
| **Decay type** | β + α | β + α | β + α | β | EC (ν) | β | α |
| **Isotop abundance** | 0, 992742 | 0,007204 | 1,0000 | $1{,}1668\cdot10^{-4}$ | 0,2822(11) | 0,1499(18) |
| **$T_{1/2}$, billion years** | 4,468(6) | 0,7038(5) | 14,0(1) | 1,248(3) | 48,1(9) | 106,0(11) |
| **μ, g/mol** | 238,051 | 235,044 | 232,038 | 39,9640 | 86,909 | |
| **$Q_{tot}$, MeV** | 51,773(17) | 46,398(10) | 42,6575(53) | 1,3116(11) | 0,283 | 2,311(1) |
| **$Q_H$, MeV** | 47,677(10) | 44,382(5) | 40,438(5) | 0,6767(17) | 0,0567(2) | 2,311(1) |
| **$\varepsilon_H$, μW·kg$^{-1}$** | 94,39(13) | 4,099(3) | 26,4(2) | $3{,}358\cdot10^{-3}$ | $8{,}11\cdot10^{-3}$ | $4{,}61(6)\cdot10^{-2}$ |
| **$\varepsilon_\nu$, kg$^{-1}$c$^{-1}$** | $7{,}41\cdot10^{7}$ | $2{,}306\cdot10^{6}$ | $1{,}63\cdot10^{7}$ | $2{,}765\cdot10^{4}$ | $0{,}332\cdot10^{4}$ | $8{,}9(2)\cdot10^{5}$ | - |

Table 1: The main contributors to radiogenic heat production. Q is the total energy released in the corresponding decay/decay chain, including the energy released by the neutrino (estimated using the latest available version of the ENSDF database [5], errors are calculated using the same database), heating energy $Q_H$ is the "visible" (dissipated for heating) release energy, namely the total released energy, excluding the fraction of energy taken by the antineutrino, specific heat $\varepsilon_H$ and specific luminosity of antineutrino $\varepsilon_\nu$ (or neutrinos in the case of capture of an electron at 40 K) per 1 kg of a naturally occurring element are presented in the last two lines, taking into account the natural content of the corresponding radioactive isotope fraction (in the case of uranium, the values for the two isotopes must be summed to obtain the total heat flux and antineutrino flux per 1 kg of natural U).

Less important branches are omitted in these graphs for the sake of simplicity (all minor details can be found in the tables). Due to the very small cross section of interaction with matter, neutrinos carry away some fraction of energy released in β-decay, and only the remaining energy of the electron and gamma radiation is converted into heat (compare the columns $Q_{tot}$ and $Q_{eff}$ in tables).

The chain of decay of uranium (historically called the “radium series”) begins with the natural $^{238}U$. It includes isotopes of astatine, bismuth, lead, polonium, protactinium, radium, radon, thallium and thorium, provided that they are all present in any uranium-containing sample. The total energy released during a single decay of $^{238}U$ into $^{206}Pb$ is 51.773±0.017 MeV, taking into account the assumption of secular equilibrium. The properties of individual decays in the $^{238}U$ chain are presented in Table 2. Natural uranium, along with $^{238}U$ and $^{235}U$, contains the decay products of $^{234}U$, which are in secular equilibrium with the parent nuclei $^{238}U$, its daughter decays are included in the calculations as part of the parental chain $^{238}U$.

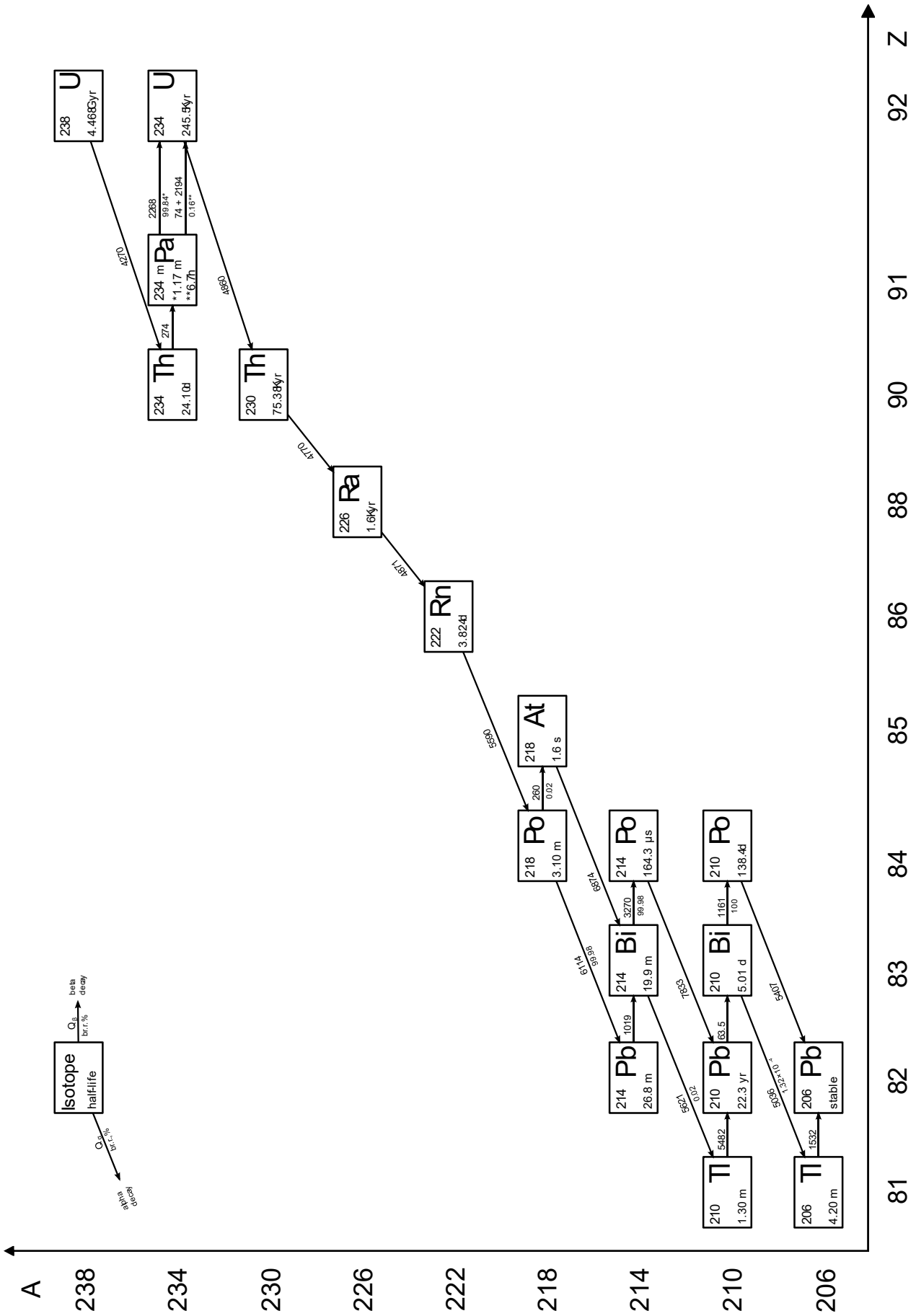


Fig.1 $^{238}$U decay chain

Another chain begins with the less common isotope – $^{235}$U (“actinium series”). This series of decays includes isotopes of actinium, astatine, bismuth, france, lead, polonium, protactinium, radium, radon, thallium and thorium. The total energy released during a single decay of parent nucleus $^{235}$U into $^{207}$Pb is 46.398±0.010 MeV, taking into account a secular equilibrium. The properties of the individual decays of the $^{238}$U chain are presented in Table 3. Two large uncertainties in the energy values of the individual decays $^{238}$U arise from the relatively large errors in the rare decay branch of the $^{227}$Ac and the decay of its daughter nucleus $^{227}$Th from an alternative branch. These uncertainties are 100% anti-correlated and practically canceled, since their values are very close.

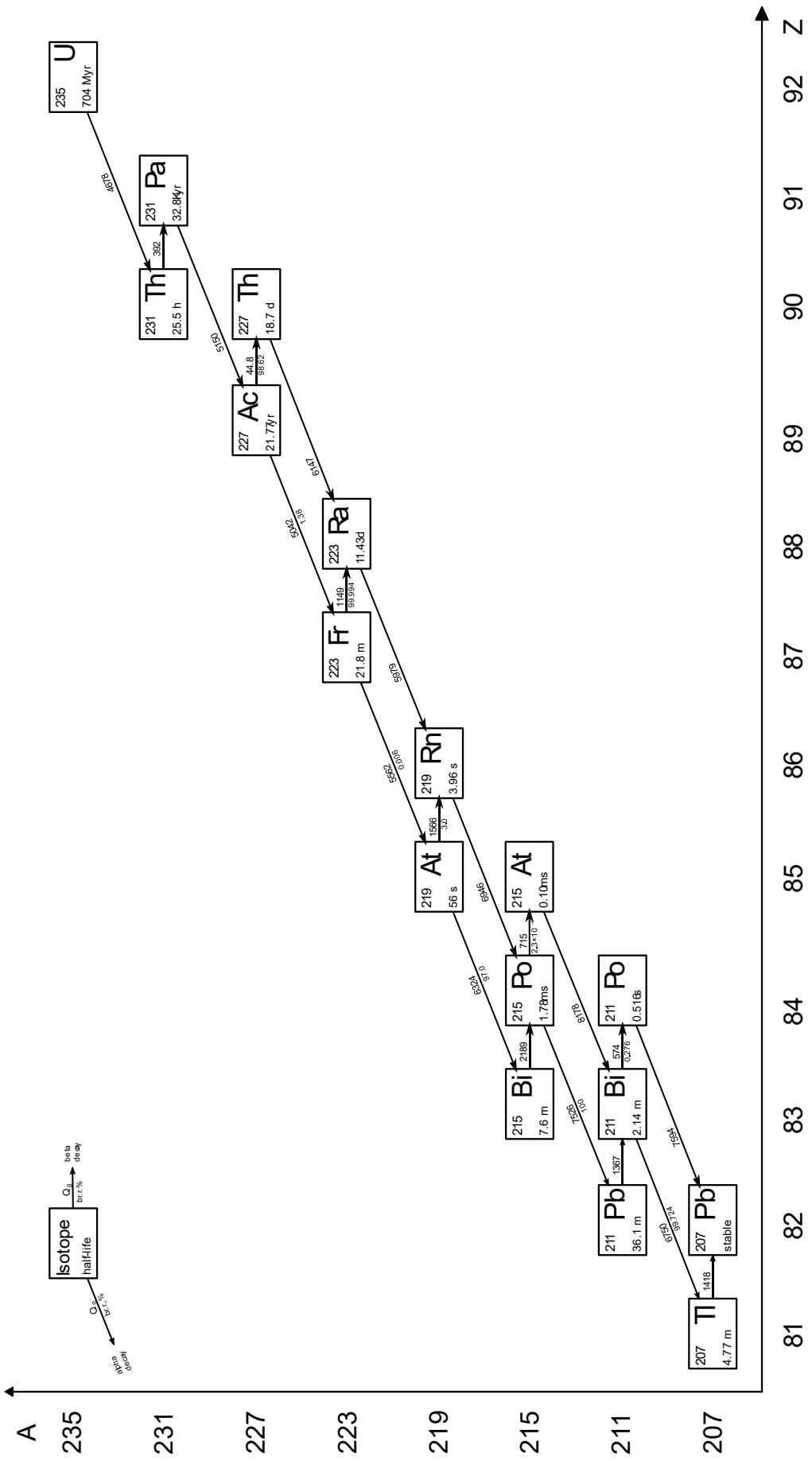


Fig.2 $^{235}$U decay chain

The last chain considered is the "thorium series" beginning with the naturally occurring $^{232}$Th. This series includes isotopes of actinium, bismuth, lead, polonium, radium and radon. The total energy released from $^{232}$Th to $^{208}$Pb is 42.6575 ± 0.0053 MeV. The properties of individual decays in the chain of $^{238}$U are presented in Table 4. $^{234}$Th decays into the metastable state of $^{234}$Pa though β-decay. $^{234}$Pa$^{m}$ in its turn decays mainly into $^{234}$U (99.84%, not more than 10 keV with Q = 2269±4 + X keV, where X <10 keV). A less probable decay (0.16%) in $^{234}$U occurs after the isomeric transition to the ground state of $^{234}$Pa with energy $Q_{IT}$ = 72.92±0.02 + X keV (X <10 keV). The low intensity isometric transition with maximum energy of less than 10 keV from $^{234}$Pa$^{m}$ to the first excited level $^{234}$Pa (explaining the 73.92 keV gamma-ray transition to the $^{234}$Pa ground state), was not observed yet, possibly because the conversion lines are obscured by intense Auger M and Koster-Kronig electrons. As a consequence, the energies of all $^{234}$Pa excited levels decaying to $^{234}$Pa$^{m}$ are known to be upheld by at most 10 keV, with a systematic uncertainty usually denoted by "X" in the data evaluations [6].

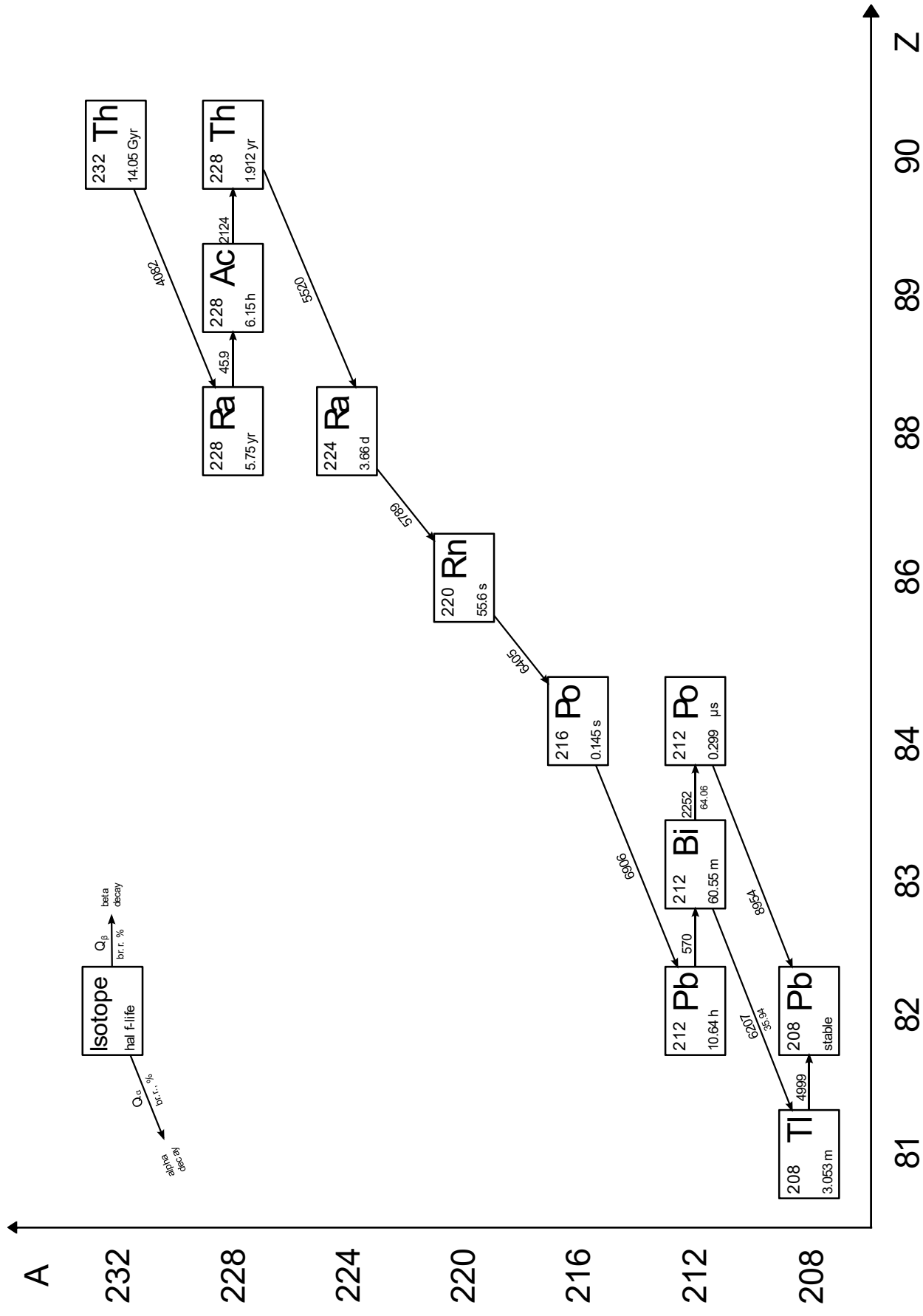


Fig.3 $^{232}$Th decay chain

β-decay $^{40}$K is unique third forbidden. In accordance with available data [5] intensity of the 1460.82 γ-line is (10.66±0.17)%, and the total EC branch has (10.72±0.13)% branching ratio, leaving for EC into the ground state (0.06±0.04)% (this decay is anticorrelated with 10.66% decay into the excited state). The EC into the ground state slightly reduces the heating energy, see Table 5 for details. The effective energy release (average energy of the β- spectrum) for $^{40}$K of $E_{eff}$ =583.6 keV, is in a good agreement with both experimental (< E >=583.98 keV, [7]) and recent calculations (<E>=583.27 keV, [8]).

The abundance of natural Rb is 400 times less than K, so its total heat is about 0.6% of the heat released by potassium. The abundance of natural Sm is 600 times less than K, so its specific heat capacity is 14 times greater than that of natural K and amounts to ~2.5% of potassium. The total heat released by Rb and Sm is about 0.1 TW, which is significantly lower than the measurement uncertainty of the total heat flux. The data for estimating energy release were taken from the latest available version of ENSDF [5].

It should be noted that while the measured values of $Q_{tot}$ have typical uncertainties below 0.1%, the estimate $Q_{eff}$ is usually less precise, since it depends on the accuracy of measuring the branch ratios for complex decays (with β-decay into excited levels of daughter elements) and shapes of β-decays.

The calculations use the universal shape of β-decay spectrum, with the exception of $^{210}$Bi in the chain $^{238}$U, β-decay of $^{40}$K (3rd forbidden unique) and of $^{87}$Rb (3rd forbidden not unique). As an illustration of the possible bias caused by the shape of the spectrum, the value $Q_{eff}$ = 0.122 MeV, obtained allowed shape, is more than twice the value calculated by the corrected shape. The total error in energy release is not affected significantly by corrections to energy shapes, since only a small part of the total energy is released in β-decays, usually less than 5% of the total energy: 2.0 out of 47.7 MeV in the $^{238}$U chain ; 1.5 out of 44.4 MeV in the $^{235}$U chain; 1.5 out of 40.4 MeV in the chain $^{232}$Th.

In conclusion, we can state that geoneutrinos are mainly born in the form of electron antineutrinos in β-decays with an admixture of electron neutrinos from electron capture. Neutrinos are produced only by the capture of electrons of $^{40}$K. Unlike the Sun, powered by nuclear fusion, the Earth "radiates" mainly antineutrinos, which are formed as a result of radioactive β-decay. In the process of neutrino propagation, its flavor is not preserved due to the oscillation mechanism, and other neutrino and antineutrino flavors may be registered or absent on the detector, depending on the detection mechanism.

| **Isotope** | **Branching, % (decay(s) type)** | **$T_{1/2}$** | **Daughter nuclear** | **Q, keV** | **$Q_{eff}$, keV** | **Rate, 1/Bq** | **$Q_{eff}$, keV** |
|---|---|---|---|---|---|---|---|
| **$^{238}$U** | 100 (α) | 4.468 Gy | $^{234}$Th | 4269.7(2.9) | - | 1.000 | 4269.7 |
| **$^{234}$Th** | 100 ($\beta^-$) | 24.10 d | $^{234m}$Pa | 273 (3) | 152.4 | 1.000 | 152.4(1.7) |
| **$^{234m}$Pa** | 0.16 ± 0.04(IT) | 1.159 m | $^{234}$Pa | 73.92(0.02+X) | 79+X | 1.6e-3 | 0.13(0.03) |
| | 99.84 ± 0.04 ($\beta^-$) | | $^{234}$U | 2269(4+X) | 812.2+X | 0.9984 | 810.9(1.4+y) |
| **$^{234}$Pa** | 100 ($\beta^-$) | 6.70 h | $^{234}$U | 2195(4) | 1746(3) | 1.6e-3 | 2.8(0.7) |
| **$^{234}$U** | 100 (α) | $2.455\cdot10^5$ y | $^{230}$Th | 4859.8(0.9) | - | 1.000 | 4859.8(0.9) |
| **$^{230}$Th** | 100 (α) | $7.54\cdot10^4$ y | $^{226}$Ra | 4770(1.5) | - | 1.000 | 4770(1.5) |
| **$^{226}$Ra** | 100 (α) | $1.6\cdot10^3$ y | $^{222}$Rn | 4870.6(0.3) | 4870.6 | 1.000 | 4870.6 |
| **$^{222}$Rn** | 100 (α) | 3.8235 d | $^{218}$Po | 5590.3(0.3) | - | 1.000 | 5590.3 |
| **$^{218}$Po** | 0.020 ($\beta^-$) | 3.098 min | $^{218}$At | 260(12) | 71.7(3.3) | 2e-4 | 0 |
| | 99.980(2) (α) | | $^{214}$Pb | 6114.7 | - | 0.9998 | 6113.5 |
| **$^{218}$At** | 0.1 ($\beta^-$) | 1.5 s | $^{218}$Rn | 2881(12) | - | 2e-7 | 0 |
| | 99.9 (α) | | $^{214}$Bi | 6874(3) | - | 2e-4 | 1.4 |
| **$^{218}$Rn** | 100 (α) | 35 ms | $^{214}$Po | 7262.5(1.9) | - | 2e-7 | 0 |
| **$^{214}$Pb** | 100 ($\beta^-$) | 26.8 min | $^{214}$Bi | 1019(11) | 528.7(6) | 0.9998 | 528.6(6) |
| **$^{214}$Bi** | 99.979 (β) | 19.9 min | $^{214}$Po | 3270(11) | 2113.2(7.1) | 0.9998 | 2112.8(7.1) |
| | 0.021 (α) | | $^{210}$Tl | 5621(3) | - | 2.1e-4 | 1.2 |
| **$^{214}$Po** | 100 (α) | 164.3 μ s | $^{210}$Pb | 7833.5 | - | 0.9998 | 7831.9 |
| **$^{210}$Tl** | 100 ($\beta^-$) | 1.30 min | $^{210}$Pb | 5482(12) | 3605.5 | 2.1e-4 | 0.8 |
| **$^{210}$Pb** | 100 ($\beta^-$) | 22.20 y | $^{210}$Bi | 63.5 | 45.3 | 1.000 | 45.3 |
| | $1.9(3)\cdot10^{-6}$ | | $^{206}$Hg | 3792(20) | - | 1.9e-8 | 0 |
| **$^{210}$Bi** | 100($\beta^-$) | 5.012 d | $^{210}$Po | 1162.2(0.8) | 308.3 | 1.000 | 308.3 |
| | $1.32(7)\cdot10^{-4}$(α) | | $^{206}$Tl | 5036.4(0.8) | - | 1.32e-6 | 0 |
| **$^{210}$Po** | 100 (α ) | 138.376 d | $^{206}$Pb | 5407.5 | - | 1.000 | 5407.5 |
| **$^{206}$Hg** | 100 ($\beta^-$) | 8.32 min | $^{206}$Tl | 1308(20) | 527 | 1.9e-8 | 0 |
| **$^{206}$Tl** | 100 ($\beta^-$) | 4.202 min | $^{206}$Pb | 1532.3(0.6) | 539.9 | 1.32e-6 | 0 |
| **$^{206}$Pb** | | stable | | 51772.8(16.8) | | | 47677.5(10.0) |

Table 2: $^{238}$U decay chain. Q is the total energy released in the corresponding decay, including the energy lost for neutrinos, rounded to keV, the corresponding error is indicated in brackets after each Q value, also rounded to 1 keV. $Q_{eff}$ - efficient energy release, full energy release, excluding neutrino energy loss. The

rate is given per 1 Bq of parental decay, the last column contains the effective energy release per 1 Bq of parental decay. [y <3.6 keV]

| **Isotope** | **Branching, % (decay(s) type)** | **$T_{1/2}$** | **Daughter nuclear** | **Q, keV** | **$Q_{eff}$, keV** | **Rate, 1/Bq** | **$Q_{eff}$, keV** |
|---|---|---|---|---|---|---|---|
| **$^{232}$Th** | 100 (α) | 1,40 · 1 0 10 y | $^{228}$Ra | 4081,6 ± 1,4 | - | 1 | 4081,6 ± 1,4 |
| **$^{228}$Ra** | 100 (β-) | 5,75 y | $^{228}$Ac | 45,8 ± 0,7 | 24,6 | 1 | 24,6 ± 0,4 |
| **$^{228}$Ac** | 100 (β-) | 6,5 h | $^{228}$Th | 2134 ± 3 | 1379,4 | 1 | 1379,4 ± 2 |
| **$^{228}$Th** | 100 (α) | 1,9116 y | $^{224}$Ra | 5520,1 | - | 1 | 5520,1 |
| **$^{224}$Ra** | 100 (α) | 3,66 d | $^{220}$Rn | 5788,9 | - | 1 | 5788,9 |
| **$^{220}$Rn** | 100 (α) | 55,6 s | $^{216}$Po | 6404,7 | - | 1 | 6404,7 |
| **$^{216}$Po** | 100 (α) | 0,145 s | $^{212}$Pb | 6906,3 ± 0,5 | - | 1 | 6906,3 ± 0,5 |
| **$^{212}$Pb** | 100 (β-) | 10,64 h | $^{212}$Bi | 569,9 ± 1,9 | 319,3 | 1 | 319,3 ± 1,1 |
| **$^{212}$Bi** | 35.94 ± 0.06 (α) | 60,55 min | $^{208}$Tl | 6207,3 | - | 0,3594 | 2230,9 ± 3,7 |
| | 64.06 ± 0.06 (β) | | $^{212}$Po | 2252,1 ± 1,7 | 933,9 | 0,6406 | 598,2 ± 0,8 |
| **$^{212}$Po** | 100 (α) | 0,299 μs | $^{208}$Pb | 8954,1 | - | 0,6406 | 5736,0 ± 5,4 |
| **$^{208}$Tl** | 100 (β-) | 3,053 min | $^{208}$Pb | 4999,0 | 3980,5 | 0,3594 | 1430,4 ± 2,4 |
| **$^{208}$Pb** | | stable | | | 42658 ± 5 | | 40438 ± 5 |

Table 3: $^{232}$Th decay chain.

| **Isotope** | **Branching, % (decay(s) type)** | **$T_{1/2}$** | **Daughter nuclear** | **Q, кэВ** | **$Q_{eff}$, кэВ** | **Rate, 1/Бк** | **$Q_{eff}$, кэВ** |
|---|---|---|---|---|---|---|---|
| **$^{40}$K** | 89,8 (β-) | 1,248(3) | $^{40}$Ca | 1310,89(6) | 0,5836 | 0,8928 | 521,0 ± 0,8 |
| | 10,66(17) (EC) | | $^{40}$Ar | 1,5040(6) | 1460,82(γ) | 0,1072 | 155,7 ± 2,5 |
| | 0,06(4) (EC) | | $^{40}$Ar | 1,5040(6) | 0 | 0 | 0 |
| | 1,00(13)·$10^{-3}$ (β+) | | $^{40}$Ar | 482,40(6) | 197,35+1022 | $10^{-5}$ | 0 |
| **Общее тепло** | | | | 1331,6±1,1 | | | 676,7 ± 1,7 |

Table 4: $^{40}$K decays

| Isotope | Abundance, % | $T_{1/2}$, b.y. | Q, keV | $Q_{eff}$, keV | Decay type | Daughter nuclear | $a_{BSE}$, ppm | H, μV/kg | H/H(K) |
|---|---|---|---|---|---|---|---|---|---|
| $^{238}$U | 99,2742 ± 0,001 | 4,47 ± 0,006 | 4269,7 ± 2,9 | 4269,7 | α(100%) | $^{234}$Th | 0,0203 | 94,39 | 2,38 |
| $^{232}$Th | 100 | 14,0 ± 0,1 | 4081,6 ± 1,4 | 4081,6 | α(100%) | $^{228}$Ra | 0,0795 | 26,4 | 2,6 |
| $^{235}$U | 0,7204 ± 0,0006 | 0,70 ± 0,01 | 4678,2 ± 0,7 | 4678,2 | α(100%) | $^{231}$Th | 0,0203 | 4,099 | 0,103 |
| $^{40}$K | 0,0117 ± 0,0001 | 1,248 ± 0,003 | 1504,40 ± 0,06 | 676,7 | EC(10,72± 0,011%) | $^{40}$Ar | 240 | $3,36\cdot10^{-3}$ | 1 |
| | | | 1310,89 ± 0,06 | | β (89,28± 0,11%) | $^{40}$Ca | | $3,36\cdot10^{-6}$ | $1\cdot10^{-3}$ |
| $^{176}$Lu | 2,599 ± 0,013 | 37,6 ± 0,07 | 1190,2 ± 0,8 | 595,1 | β(100%) | $^{176}$Hf | 0,0675 | $4,95\cdot10^{-3}$ | $4,14\cdot10^{-4}$ |
| $^{115}$In | 95,71 ± 0,05 | $(4,41\pm 0,25)\cdot10^{5}$ | 497,489 ± 0,01 | 248,7 | β(100%) | $^{115}$Sn | 0,011 | $9,95\cdot10^{-6}$ | $1,36\cdot10^{-7}$ |
| $^{113}$Cd | 12,22 ± 0,12 | $(8,0 \pm 0,3)\cdot10^{6}$ | 322 ± 1 | 161 | β(100%) | $^{113}$In | 0,04 | $4,61\cdot10^{-8}$ | $2,29\cdot10^{-9}$ |
| $^{87}$Rb | 27,83 ± 0,02 | 49,7 ± 0,3 | 232,2 ± 1,1 | 116,1 | β(100%) | $^{87}$Sr | 0,6 | $7,74\cdot10^{-3}$ | $5,75\cdot10^{-3}$ |
| $^{138}$La | 0,08881 ± 0,00071 | 102 ± 1 | 1742 ± 3 | 871 | EC (65,5± 0,4%) | $^{138}$Ba | 0,648 | $1,16\cdot10^{-4}$ | $9,35\cdot10^{-5}$ |
| | | | 1052 ± 4 | 526 | β(34,5± 0,4%) | $^{138}$Ce | | $7,03\cdot10^{-5}$ | $5,65\cdot10^{-5}$ |
| $^{187}$Re | 62,6 ± 0,02 | 43,3 ± 1,0 | 2,469 ± 0,004 | 1,2 | β(100%) | $^{187}$Os | 0,00028 | $2,02\cdot10^{-4}$ | $7,02\cdot10^{-8}$ |
| $^{123}$Te | 0,89 ± 0,03 | $9,2\cdot10^{7}$ | 52,2 ± 1,5 | 26,1 | EC(100%) | $^{123}$Sb | 0,012 | $4,35\cdot10^{-11}$ | $6,47\cdot10^{-13}$ |
| $^{152}$Gd | 0,2 ± 0,01 | $1,08\cdot10^{5}$ | 2204,9 ± 1,4 | 2204,9 | α(100%) | $^{148}$Sm | 0,544 | $5,69\cdot10^{-7}$ | $3,84\cdot10^{-7}$ |
| $^{148}$Sm | 11,24 ± 1 | $(7\pm3)\cdot10^{6}$ | 1986,0 ± 1,2 | 1986 | α(100%) | $^{144}$Nd | 0,406 | $4,57\cdot10^{-7}$ | $2,3\cdot10^{-7}$ |
| $^{144}$Nd | 23,798 ± 0,019 | $(2,29\pm 0,16)\cdot10^{6}$ | 1928,1 | 1928,1 | α(100%) | $^{140}$Ce | 0,00125 | $2,9\cdot10^{-6}$ | $4,57\cdot10^{-9}$ |
| $^{147}$Sm | 14,99 ± 0,18 | 106,0± 1,1 | 2311 ± 1 | 2311 | α(100%) | $^{143}$Nd | 0,406 | $4,61\cdot10^{-2}$ | $2,32\cdot10^{-2}$ |
| $^{174}$Hf | 0,16 ± 0,01 | $(2,0 \pm 0,4\cdot10^{6}$ | 2519,9 | 2519,9 | α(100%) | $^{170}$Yb | 0,283 | $2,45\cdot10^{-8}$ | $8,61\cdot10^{-9}$ |
| $^{190}$Pt | 0,012 ± 0,002 | 650 ± 30 | 3249 ± 6 | 3249 | α(100%) | $^{186}$Os | 0,0071 | $6,69\cdot10^{-6}$ | $5,88\cdot10^{-8}$ |
| $^{186}$Os | 1,59 ± 0,03 | $(2 \pm 1,1)\cdot10^{6}$ | 2847 | 2847 | α(100%) | $^{182}$W | 0,0034 | $2,58\cdot10^{-7}$ | $1,09\cdot10^{-9}$ |

Table 5: Radiogenic heat. $^{238}$U, $^{235}$U and $^{232}$Th are entire decay chains, $^{40}$K and $^{87}$Re are isotopes of β-decay or electron capture, $^{123}$Te - only electron capture, while $^{152}$Gd and $^{186}$Os are α-decaying isotopes. $M_{Earth} = 5.97\cdot10^{24}$ kg, $M_{BSE} = 4.0\cdot10^{24}$ kg, and $M_{core} = 1.93\cdot10^{24}$ kg

# 4. Summary

In our work we obtained the following results:

- the decay chains of the most common radioactive elements in the Earth's crust are investigated;
- the total energy release in each of the chains taking into account the decay probabilities and errors has been calculated;
- the radioactive elements that contribute to the heat generation of the Earth ($^{238}$U, $^{232}$Th, $^{40}$K, $^{87}$Rb, $^{147}$Sm) are identified and heat release is evaluated. The resulting assessment results for the most part coincide within the margin of error with the results of other authors (Tables 1,6). Calculations results are presented in the article «Experimental aspects of geoneutrino detection: Status and perspectives» by O. Smirnov [4].
- To complete this work, the literature presented in references was studied and how to work with nuclear tables was learned.

| **Author** | **H, μВт/кг** | | | | |
|---|---|---|---|---|---|
| | **238 U** | **235 U** | **232 T** | **40 K** | **87 Rb** |
| **S. Enomoto (2006) [3]** | 94,5 | 4,06 | 26,3 | $3{,}29 \cdot 10^{-3}$ | $1{,}7 \cdot 10^{-2}$ |
| **G. Fiorentini (2007) [9]** | 94 | 4 | 27 | $3{,}33 \cdot 10^{-3}$ | $1{,}7 \cdot 10^{-2}$ |
| **S. T. Dye (2012) [10]** | 94,4 | 4,09 | 26,3 | $3{,}33 \cdot 10^{-3}$ | - |
| **C. Jaupart (2015) [11]** | 94,4 | 4,09 | 26,3 | $3{,}33 \cdot 10^{-3}$ | - |
| **T. Ruedas (2017) [12]** | 93,9 | 4,09 | 26,4 | $3{,}43 \cdot 10^{-3}$ | - |
| **Our results** | 94,39(13) | 4,099(3) | 26,4(2) | $3{,}36 \cdot 10^{-3}$ | $7{,}74 \cdot 10^{-3}$ |

Table 6: Comparison of calculations of H, μV/kg from different sources

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