On soil activation by cosmic rays at different altitudes

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Abstract

Measuring radon-due neutron flux at various altitude (100, 1000, 1700, 4300 m above sea level) we found an evidence of significant increase of radon concentration with altitude. It was also confirmed by direct radon measurements at high altitude. This allowed us to assume cosmic rays could take part in process of soil activation: they transform long-lived nuclei of uranium and thorium to nuclei with shorter life-time through specific nuclear reactions. If the resulting nuclei belong to the U-238 radioactive chain they can lead to production of Ra-226 and then to Rn-222, thus significantly increasing its production at high altitudes where cosmic ray flux is high.

keywords: thermal neutron; radon; cosmic rays

1 Introduction

The theory on natural radioactivity postulates that radionuclides (for example \( ^{222}Rn \)) are in equilibrium with their parents in radioactive decay chain. There are known four main radioactive chains, starting from long-lived nuclides: U-238, Th-232, U-235 and Np-237. Rn-222 is product of U-238 decay chain, so it has to be in equilibrium with it’s long-lived parents. It means that quantity of this nuclide depends only on quantity of U-238 randomly spread over the Earth crust. While measuring natural thermal neutron flux at sea level we noticed that it’s barometric coefficient is \( \sim 0.8-0.9\%/\text{mm Hg} \). On one hand we know that barometric coefficient of cosmic ray hadrons is \( \sim 1\%/\text{mm Hg} \). On another hand we assume that there are two main natural neutron flux sources: cosmic ray hadrons (producing evaporation neutrons in collisions with nuclei of soil and air, those are thermalized later) and natural radioactivity (\( \alpha \)-decay nuclei, resulting in neutrons production in \((\alpha, n)\) reaction). Taking above into account we can suppose that natural neutron flux consists by \( \sim 80-90\% \) of neutrons produced by cosmic rays and 10-20\% by natural radioactivity [1]. We have tested this assumption measuring thermal neutron flux underground: at a level of \( \sim 2.5 \text{ m of soil} \), barometric coefficient is \( \sim 0.6-0.7\%/\text{mm Hg} \). Later we have measured thermal neutron flux at few different altitudes: 1000 m (Grand Sasso, Italy), 1700 m (Baksan, Russia), 3600 m (Lhasa, Tibet, China), 4300 m (Yangbajing, Tibet, China). We supposed that a fraction of neutrons produced by cosmic ray hadrons has to grow up with altitude because cosmic ray flux rises with altitude while natural radioactivity supposed to have no such dependence. But as we have found: barometric coefficient does not depend on altitude [1]. The reason of such behavior could be found if one supposes that quantity of natural radioactive nuclides producing neutrons is also in equilibrium with integral cosmic ray flux accumulated for a long periods (thousands years). In other words:
quantity of radioactive nuclides in upper layer of soil is also proportional to cosmic ray flux and should increase with altitude. It has been confirmed by radon meters data obtained at Yangbajing (4300 m). Concentration of radon and thus quantity of α-active nuclides there is ~ 8 times higher than in Moscow or in Beijing. Let’s try to explain it.

2 Hypothesis

Our hypothesis is really simple. Let us consider two the most rife radioactive chains. U-238 has a half-life \( t = 4.47 \times 10^9 \text{years} \) and it is the second of most common heavy radionuclide in Earth crust. Th-232 has half-life \( t = 1.41 \times 10^{10} \text{years} \) and it is the first one. Rn-222 is a product of U-238 decay chain and in common view it is in equilibrium with U-238. Now let us look to reactions

\[ ^{232}\text{Th}(n,3n)^{230}\text{Th} \]

and

\[ ^{232}\text{Th}(\gamma,2n)^{230}\text{Th} \]

The first one has cross section \( \sigma \approx 0.85 \pm 0.15 \text{ barns} \) [2] and the second one \(- \sigma = 0.3 \pm 0.05 \text{ barns} \) [3,4,5] for neutrons and \( \gamma \) with \( E \approx (14 - 15)\text{MeV} \). These reactions result in production of Th-230 belonging to the U-238 decay chain and having half-life \( t = 7.7 \times 10^4 \), i.e. by a factor of 6*10^4 higher than U-238 has. Therefore, the production rate of Ra-226 being both product of Th-230 decay and parent nuclide for Rn-222, would be much higher. On the other hand, neutrons and gammas of energy \((10-20)\text{ MeV}\) are produced by cosmic rays in upper layer of soil (4-5 m). It means that concentration of Th-230, Ra-226, Rn-222 (and its products) in upper soil layer and thus flux of radon-due neutrons, should increase with long-term cosmic ray integral flux, while immediate neutron flux is proportional to immediate cosmic ray flux. It is obvious that ratio of immediate to accumulated cosmic ray fluxes does not depend on altitude in the first approximation.

3 Simulation

Using modern GEANT4.10 package code we have simulated soil containing 0.0013% of Th-232 (it corresponds to average natural quantity) bombarded with neutrons of energy 20 MeV. We searched for number of produced Th-230 nuclei. As a preliminary result we obtained \( n \approx (2 \pm 1.4) \times 10^{-6} \) nuclei of Th-230 per 1 neutron of 20 MeV. Therefore, these reactions do exist and we have to simulate these processes in more details.

4 Experimental results

Averaged counting rate of radon meters used by ARGO collaboration [6] in YangBaJing guest house rooms and open experimental hall was \( \sim 400 \text{ Bq/m}^3 \). It is much higher than in buildings at the sea level in Europe (for example Netherlands) \( \sim 40 \text{ Bq/m}^3 \). Also radon activity in Switzerland in Alps is \( \sim 200 \text{ Bq/m}^3 \) [7]. By our measurements counting rate of neutron detectors is \( \sim 8 \) times higher in YBJ than that at sea level [8]. It means that at 4300 m a.s.l. concentration of Th-230 nuclei is approximately 8 times higher than at sea level.
5 Conclusion

We suggest here a way to explain very high Rn concentration at high altitudes. Cosmic ray neutrons and gamma-quanta’s produce Th-230 from soil Th-232 due to nuclear reactions and thus increase radioactivity of upper soil level and accelerate natural decay chain process by a factor of $\sim 10^5$. Such a large factor can compensate low probability of the above reactions and can result in significant acceleration of the Th-230 production rate. This reactions replace radioactive nuclei of Th-232 family with nuclei of U-238 chain family resulting in Rn-222 production. It leads to significant increase of Rn-222 concentration in high mountains due to exponential increase of the cosmic rays flux with altitude. This hypothesis is confirmed by our preliminary GEANT4.10 simulations and experimental measurements of radon flux and thermal neutron flux at different altitudes.

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