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GEOCHEMISTRY

^{3}He Distribution in the Lunar Regolith Core Taken by the Luna 24 Unmanned Spacecraft

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As is known, the thermonuclear reaction with the application of ^{3}He is highly efficient and ecologically unique. In contrast to fission reactions and thermonuclear synthesis with the participation of deuterium and tritium (D + T), which are accompanied by the release of neutrons, the reaction D + ^{3}He = ^{4}He (3.67 MeV) + p (14.68 MeV) proceeds with the release of protons. The neutron flux leads to induced radioactivity of construction materials, their radiation damage, and the necessity of burial of large volumes of radwastes. Since protons are charged particles, they do not penetrate deep into the surrounding materials and induce radioactivity except for the relatively weak influence of the side reaction D + D. Thus, the hazard of radionuclide contamination of the environment drastically diminishes, and the problem of radwaste accumulation is eliminated. The yield of the major portion of thermonuclear energy in the form of protons substantially facilitates engineering solutions of energy utilization.

The amount of ^{3}He available on the Earth is insufficient for development of thermonuclear power stations based on this isotope. At the same time, virtually inexhaustible ^{3}He resources are available on the Moon. If thermonuclear synthesis based on ^{3}He will successfully be realized with the economic-scale production of energy, it will be necessary to carry out mining work on the Moon for the extraction and transportation of ^{3}He to the Earth. It is suggested that this problem will be topical within the next few decades [1–3].

In this connection, it would be helpful to check our knowledge about lunar ^{3}He and to plan and organize the respective research and exploration works.

In this communication, we present new data obtained from measurements of helium isotopic composition (^{3}He/^{4}He) and He contents in the lunar regolith delivered by the Luna 24 unmanned spacecraft in 1976.

The regolith was taken in the southeastern Mare Crisium (Fig. 1). The coordinates of the landing site are 12°45′ N and 62°12″ E [4]. The Mare Crisium is a giant depression with a distinct ring structure (about 500 km in diameter) formed as the result of the impact of a large body and filled with basaltic lavas. The surrounding highlands are composed of rocks of the anorthosite–norite–troctolite series. In the Luna 24 landing site area, the Mare Crisium represents a slightly NW-inclined basaltic plain studded with craters. The landing site is situated 18 km east of the Fahrenheit Crater (6.2 km in diameter) and approximately 40 km west of the highland boundary.

The regolith was sampled as a core ~2 m long. Drilling was conducted to a depth of 225 cm from the surface.

The results of analysis are given in the table.

Helium was extracted from <80 μm fraction in the preliminary degassed reactor at 1200°C. The residual background was ~10^{-9} cm^3 for ^{4}He and 10^{-13} cm^3 for ^{3}He. Then, the lunar sample was placed into the degassed reactor and left there for 10 min at 12°C. After separating the accompanying gases, the purified He was introduced into a mass spectrometer.

The isotopic analysis of ^{3}He/^{4}He was performed with a high-resolution resonance mass spectrometer at the Ioffe Physicotechnical Institute. The high resolution made it possible to separate the ^{3}He peak from the mul-

Helium isotopic composition and ^{3}He content in the lunar regolith core taken by the Luna 24 unmanned spacecraft

Sampling depth, cm	^{3}He, ppb	^{3}He/^{4}He · 10^4
72	1.3	3.03
92	1.2	3.03
130	1.4	3.11
160	1.6	2.89
192	0.8	2.84

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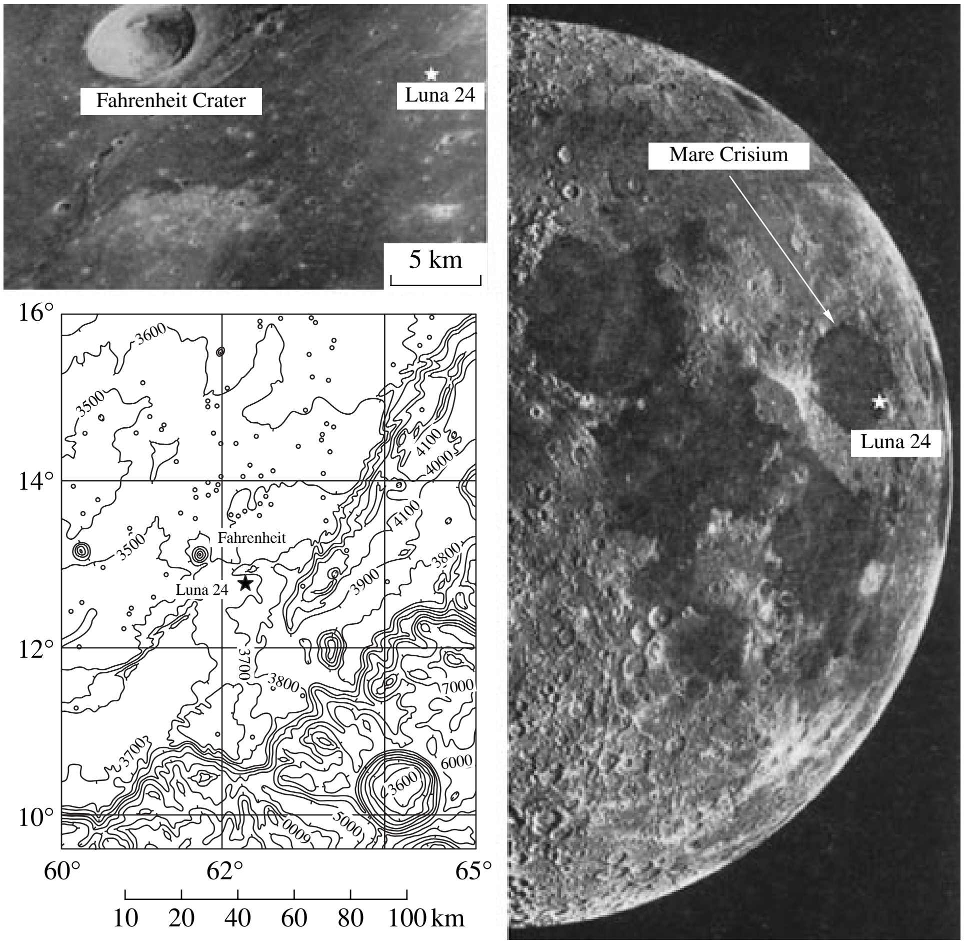

Location of the Luna 24 unmanned spacecraft landing.

tiple H_3 and HD peaks with the same mass number. The sensibility of mass spectrometer was ~$3 \cdot 10^{-13}$ cm^3 for ^{3}He. The measurements were carried out in the standard–sample two-beam regime.

Despite the clearly expressed layering of the regolith, its chemical composition is virtually similar throughout the entire core: up to 19 wt % Al_2O_3, ~1 wt % TiO_2, and 16–20 wt % FeO. Thus, the lunar soil matches basalt with elevated contents of Al and Fe and low content of Ti.

The age of mare basalts corresponding to outcrops of the Swift Basalt around the Luna 24 landing site based on crater studies is estimated at approximately 3.5 Ga [5]. The isotopic age of crystallization of a gabbro fragment from the Luna 24 regolith yielded 3.3 ± 0.05 Ga [6]. The relatively low ratio of agglutinates and grains of primary igneous rocks in the regolith indicates its immature character. Lithic fragments are largely composed of gabbro, fine-grained basalt, and dolerite. Particles from the adjacent highlands occupy no more than 1–3%.

According to the description of the Luna 24 regolith, the agglutinate content (i.e., exogenic effect) decreases with depth. However, this trend is not expressed in the distribution of ^{3}He contents.

As follows from other data on the He isotopic composition in the Luna 24 regolith [7], the ^{3}He/^{4}He ratio typical of the solar wind (~$(3.8–4.8) \cdot 10^{-4}$) is confined to the very fine-grained regolith fraction (<74 μm). In coarser grained fractions, the He content is an order of magnitude lower, whereas the ^{3}He/^{4}He ratio increases, obviously, due to the predominance of cosmic helium in these fractions.

Gases of the solar wind are implanted into a thin (~0.2 μm) surficial layer of regolith grains. As a result, the gas content is inversely correlated with the size of the regolith fraction. Therefore, <50 μm fraction should be regarded as the representative fraction in terms of He content. The ^{3}He/^{4}He ratio in the captured lunar helium is close to 2600.

The measured ^{3}He contents in the regolith are lower than the previously published results for Luna 24 [7], probably owing to a partial loss of He from the samples stored for 30 years.

In the regolith sample delivered with the Luna 16 unmanned spacecraft from the Mare Fecunditatis, the He content in the regolith was determined at (17.0–19.5) $\cdot 10^{-2}$ cm^3/g and the $^3He/^4He$ ratio was estimated at ~$3.8 \cdot 10^{-4}$ [8]. Thus, the ^3He content is 8.6–9.8 ppb. Soil from Mare Fecunditatis is composed of high-Ti basalt.

In the Luna 20 regolith taken from the highland between Mare Crisium and Mare Fecunditatis, the He content in the fraction <44 μm is $3.81 \cdot 10^{-2}$ cm^3/g [9], which corresponds to 2.6 ppb based on recalculation for the captured ^3He content. According to [10], the maximum ^4He content in the fine fraction is 4.7–8.3 cm^3/g, i.e., approximately 3.3–5.9 ppb of solar ^3He.

The results of ^3He measurements in the samples delivered by the Apollo missions are summarized in [2]. The composite regolith sample (38.5 kg in mass) was taken by the astronaut N. Armstrong from different (>20) sites over a total area of 15 m^2 during the Apollo 11 mission. The ^3He content in this composite sample varied from 9.22 to 17.9 ppb (11.8 ppb, on average).

The ^3He content measured in eight samples of regolith breccia taken during the Apollo 11 mission varied from 4.38 to 18.2 ppb (12.7 ppb, on average). The TiO_2 content in basalts from Mare Tranquillitatis and, in particular, at the Apollo 11 sampling site is estimated at 7.5 wt %, on average.

The regolith cores were taken at 21 sites for all six Apollo missions on the lunar surface. The core depth generally varied from 10 to 40 cm [11]. Two cores were drilled to depths of 237 and 221 cm during the Apollo 15 and 16 missions, respectively. The deepest core (239 cm) was obtained by the astronaut–geologist H. Schmitt during the Apollo 17 mission. In the samples taken during this mission, the ^3He content varied from 9.9 to 14.3 ppb in the fine regolith fraction (<20 μm). The ^3He content in the fraction >200 μm was only 1.08–1.44 ppb. In the regolith breccia, the ^3He content varied from 15.6–16.3 ppb in the fraction <20 μm to 1.4 ppb in the fraction >200 μm.

Thus, the available information and new data indicate that the ^3He content amounts to 10–20 ppb in the areas covered by high-Ti basalts that are typical of the Moon (Luna 16 and Apollo landing sites). In the highlands and in the areas covered by low-Ti basalts (Luna 20 and Luna 24 landing sites, respectively), the ^3He content in the regolith is 0.5–2.0 ppb. The average ^3He content in the upper regolith layer of the Moon is apparently ~4 ppb.

The ^3He content in the fine fraction (<50 μm) is an order of magnitude higher than that in the submillimeter fraction (>200 μm).

Thus, the search for ^3He should be focused, first of all, on the high-Ti basalt fields with a mature regolith and high content of fine fraction (<50 μm).

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