PHYSICAL REVIEW VOLUME 91, NUMBER 6 SEPTEMBER 15, 1953

Effects of a Primeval Endowment of U^{236}†

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(Received February 13, 1953)

The effects of a primeval endowment of U^{236} upon theories pertaining to the evolution of the elements, the thermal history of the earth, and geochronology are considered. It is shown that the present thorium to uranium ratio, early volcanism on the earth and on the moon, as well as corrections to the dating of rocks and meteorites may be related to an initial abundance of the isotope, if certain assumptions are made.

RECENT measurements[1,2] indicating that the half-life of U^{236} is approximately 2.4×10^7 yr should be taken into account in formulating theories pertaining to the evolution of the elements, the thermal history of the earth, and geochronology.

A survey of radioactive isotopes shows that known half-lives fall into two classes; (a) those of the same order or longer than the age of the earth, (b) half-lives of insignificant duration on a geological scale. Class (a) contains Th^{232}, U^{238}, Rb^{87}, La^{138}, Sm^{147}, Lu^{176}, and Re^{187}. Also included in this class are U^{235} and K^{40} which possess half-lives of the order of 10^8 or 10^9 yr and, consequently, have been seriously depleted during the earth's 3 or 4 billion years of existence but still persist to a detectable degree. Class (b) contains radioisotopes which occur naturally only by virtue of their constant generation as members in a radioactive series initiated by the decay of one of the substances of class (a), others such as C^{14} or Pu^{239} which are constantly generated by stray neutrons, as well as the artifically produced radioisotopes. U^{236} is unique in belonging to neither class; its half-life relative to the age of the earth is too short to result in a detectable abundance of this isotope in natural uranium, yet it is sufficiently long to insure its existence during the first part of the earth's history. Given an initial endowment of U^{236}, we must consider it to have persisted as a significant entity during the first half-billion years of geological time, for its half-life is not entirely negligible in relation to current estimates of the time interval between the genesis of the elements and the formation of the earth.[3]

The interval between element formation and formation of the earth's atmosphere has been estimated by Katcoff, Schaeffer, and Hastings[4] to be 0.27×10^9 yr and by Suess and Brown[5] to be of the order of 0.4×10^9 yr. Most of the following effects are predicated upon the possibility that these estimates for the interval are too high, or that the earth, as an entity, is appreciably older than its atmosphere.

Owing to the lack of any generally accepted theory concerning the formation of the elements, one cannot postulate an initial endowment of U^{236} in planetary matter with any degree of certainty. However, an initial abundance of U^{235} comparable to that of the main uranium isotope has often been invoked in estimating the age of the earth; there is nothing in the systemics of nuclei to suggest that U^{236}, with an even number of neutrons and protons, and lying closer in mass to the most stable isotope, U^{238}, should have been formed less abundantly than U^{235}. U^{236} is highly fissionable when in a sufficiently excited state; consequently it could only have been formed if the element building process produced the isotopes in their final distribution after the temperature of the nuclei had subsided to low values. Theories which assume that the various nuclides originated as aggregates of neutrons and, subsequently, were transformed through successive beta decay into the naturally occurring isotopes[6] appear to be consistent with an appreciable initial abundance of U^{236}. Although the production of U^{236} in piles is a low yield process, the absorption of a neutron in U^{235} generally imparting sufficient energy to the compound nucleus to result in fission, the opposite would hold for the primeval production through successive beta decay; for in the latter case, the final U^{236} nucleus would not be sufficiently excited to undergo fission. In fact any theory of element building in which the accumulation of the positive charge within the nucleus necessary for the fission process occurs after the universe has passed through the stages of very high density and temperature should result in an original U^{236} endowment in the same way that it leads to a finite abundance for U^{238} and other isotopes for which the values of Z^2/A are not so large as to result in prohibitive rates of spontaneous fission.

Virtually the entire original endowment of U^{236} must have decayed through alpha emission to Th^{232} during the first half-billion years of geological time. Consequently, we should not look for any U^{236} in present analyses of natural uranium, but, instead, should expect to find an enrichment of Th^{232} relative to other nuclides in this portion of the abundance curve of the

† Work done at Brookhaven National Laboratory, Upton, New York, under contract with the U. S. Atomic Energy Commission.

[1] Jaffey, Diamond, Hirsh, and Mech, Phys. Rev. **84**, 785 (1951).

[2] Fleming, Ghiorso, and Cunningham, Phys. Rev. **88**, 642 (1952).

[3] G. Gamow and C. L. Critchfield, *Theory of Atomic Nucleus and Nuclear Energy-Sources* (Oxford University Press, London, 1949), pp. 307 and 309.

[4] Katcoff, Schaeffer, and Hastings, Phys. Rev. **82**, 688 (1951).

[5] H. E. Suess and H. Brown, Phys. Rev. **83**, 1254 (1951).

[6] G. Gamow, Phys. Rev. **70**, 572 (1946).

elements. In Goldschmidt's survey[7] we find that thorium is, indeed, more common throughout the universe than the nearby elements uranium and bismuth. Assuming that, originally, equal numbers of atoms of uranium and thorium were formed, and that uranium consisted chiefly of U^{235}, U^{236}, and U^{238}, in roughly equal quantities, the U^{235} would largely decay to Pb^{207} and the U^{236} would, in its entirety, decay to Th^{232} resulting in a present thorium to uranium ratio of 4, which, even after correction for the partial decay of U^{238}, is still in rough agreement with the value of 3.8 commonly quoted for "average" rocks.

Any appreciable original abundance of U^{236} should have severely affected the early thermal history of the earth. For example, Urey's theory of the formation of the earth by accretion, melting due to radioactive heating, and final cooling[8] would have to be modified and allowance made for two distinct periods of heat production. Due to the relatively enormous disintegration rate of U^{236}, the heat generation in the earth immediately after accretion should have been very great; in fact during the first half-billion years the earth would probably have to be regarded as molten even at the center. As the amount of U^{236} dwindled, temperatures should have dropped to the point where pressure sufficed to insure a semisolid phase at the earth's core. The disintegrations of K^{40} and the $4n+2$, $4n$ and $4n+3$ series should have continued to maintain the molten magma still found at moderate depths.

An original abundance of U^{236} would affect the thermal history of the moon differently owing to the larger surface to volume ratio and lower thermal inertia of the satellite. Heating due to K^{40} and to U^{238}, U^{235}, and Th^{232} and their descendants is insufficient to lead to high internal temperatures, as is demonstrated by the total lack of volcanism on the moon at the present time. However, initially the high disintegration rate of U^{236} may have resulted in formation of the moon's craters. Volcanism on a scale necessary to produce such craters is symptomatic of enormous temperature gradients at a time when the outer crust was already formed. (In the case of the earth no large craters should be expected, for the greater volume to surface ratio and thermal inertia would conserve the heating due to ordinary uranium and thorium thereby maintaining the crust in a molten state after most of the U^{236} had decayed.)

These remarks are based on purely qualitative considerations owing to the difficulty of arriving at reasonable estimates for the thermal conductivities, as well as the roles of convection currents and orogeny, in determining the rate of heat transfer to the surfaces of the earth and the moon during their very early history.

A possible primeval endowment of U^{236} must be taken into account in evaluating methods of geochronology based upon relative abundances of uranium and lead isotopes, as well as those depending upon helium content. For example, Holmes' method leads to certain values for the abundances of the lead isotopes at the time of formation of the earth's crust.[9] Alpher and Herman have shown how to derive these abundances using three basic equations.[10] The equations assume a simple decay of thorium and uranium within the source magma prior to deposition of a lead sample. A primeval endowment of U^{236} would change the form of the third equation by requiring that the simple decay of thorium be replaced by a sharp initial rise, followed by decay. Estimates of the ages of various geological formations and of the age of the earth's crust would not be appreciably affected, since in general a least squares analysis is used which largely eliminates the dependence upon the early abundances of uranium and thorium. On the other hand, the use of present lead isotope ratios in calculating the abundances of Th^{232} and Pb^{208} at the time of origin of the elements would have to be revised. The effect on the former is large and has been discussed earlier in this paper; the effect on the latter would be quite small, but any change would be of interest from the point of view of nuclear shell structure.[11]

Helium age methods as applied to terrestrial samples should not be affected, for such determinations have not been found to be reliable for ages earlier than pre-Cambrian, in any case. However, a primordial abundance of U^{236} would require a modification of helium methods as applied to meteorites, at least in the case of samples whose age is assumed, or found, to exceed 10^9 yr. After subtraction of that part of the He content formed within the meteorite by cosmic rays, as described by Singer,[12] it would be necessary to adjust the remainder so as to allow for emission of one alpha particle in the case of the one out of every four Th^{232} nuclei which had originated as U^{236}. Since only a minority of all the Th^{232} nuclei decay during the life of a meteorite, the correction should be significant.

[7] V. M. Goldschmidt, *Verteilungsgesetze der Elements* (Oslo, 1938).
[8] H. C. Urey, *The Planets* (Yale University Press, New Haven, 1952).
[9] A. Holmes, Nature **157**, 68 (1946).
[10] R. Alpher and R. Herman, Phys. Rev. **84**, 1112 (1951).
[11] R. Alpher and R. Herman, Phys. Rev. **84**, 1113 (1951).
[12] S. F. Singer, Nature **170**, 728 (1952).