WHAT DOES THE NUCLEAR CHRONOMETRY SAY ON REAL AGE OF STARS AND EARTH?

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We consider the factors which essentially influence the results of measurements of the effective duration of decomposition of a large massif of matter containing long-living radioactive chronometric nuclei that still have not been taken into consideration. For the first time, the contribution of alpha-particles' knocking out into the reduction of the half-life period of chronometric nuclei at the Earth's surface is considered for specific models of interaction between cosmic protons and chronometric nuclei. The results obtained give an evidence for that the Earth's age may be less by several orders of magnitude as compared with the previous estimations.

1. What is a Nuclear Cosmic Chronometry?

The age estimations for the Universe as 10 or 20 billion years and for the Earth as 4 or 5 billion years are now considered to be the most reliable. They have been obtained by using the technique of nuclear cosmic chronometry with taking into account a decay of long-living radioactive nuclei staying in the ground states and surrounded by the completed electron shells of corresponding neutral atoms.

A wide range of long-living radioactive nuclei is used as chronometers for duration measurements of astrophysical, cosmological, and geophysical processes. More exactly, the chains of sequential radioactive decays of all intermediate nuclei are used for this purpose, beginning from the parent nuclei and ending with the stable ones. A large-scale nuclear clock usually consists of the following long-living isotopes: beta-radioactive nuclei of ^{40}K, ^{87}Rb, ^{176}Lu, and ^{187}Re (with the half-life periods of $1.3 \cdot 10^9$, $4.7 \cdot 10^{10}$, $2.6 \cdot 10^{10}$, and $4.3 \cdot 10^{10}$ years, correspondingly, in the ground states of neutral atoms, and with final stable nuclei ^{40}Ar, ^{87}Sr, ^{176}Hf, and ^{187}Os of the formed atoms or ions, correspondingly), and alpha-radioactive nuclei ^{232}Th and ^{238}U (with the half-life periods of $1.4 \cdot 10^{10}$ and $4.5 \cdot 10^9$ years in the ground states and with final stable nuclei ^{208}Pb and ^{206}Pb, correspondingly).

The main principle of the nuclear chronometry technique (see, for instance, [1]) consists in a measurement of the isotope relationships in earth rocks, meteorite fragments, etc., which change in time because of the decay of long-living radioactive nuclei. Specifically, the procedure of a sample age determination may be described as follows. Variation in time (i.e., dependence on the difference $t - t_0$ with t_0 being the sample's formation moment) of the quantity (or mass) $P(t - t_0)$ of the decaying initial nuclei is described by the known exponential formula

$$P(t - t_o) = P(0) \exp[-(t - t_0)/\tau], \quad (1)$$

where τ is the average lifetime connected with the half-life period $T_{1/2}$ by the relationship $\tau = T_{1/2}/\ln 2$. Initial radioactive nuclei do experience, as a result of decay, a transformation into final stable nuclei, whose quantity (or mass) we denote as $D(t - t_0)$. Apparently, the total sum of $P(t - t_0)$ and $D(t - t_0)$ does not change in time, i.e.

$$P(t - t_0) = P(0) \exp[-(t - t_0)/\tau]. \quad (2)$$

That gives us the following relationship:

$$P(0)\{1 - \exp[-(t - t_0)/\tau]\} - D(t - t_0) + D(0) = 0 \quad (3)$$

or

$$P(t-t_o)\{\exp[(t-t_0)/\tau]-1\}-D(t-t_0)+D(0)=0. \tag{3a}$$

After this, we divide Eq. (3a) by the quantity (mass) D_x of another isotope of the stable final nucleus, which is not contributed from the decomposition of initial nuclei (i.e., D_x is independent of time). As a result, Eq. (3a) transforms into the relationship

$$p(t-t_0)\{\exp[(t-t_0)/\tau]-1\}-d(t-t_0)+d(0)=0, \tag{3b}$$

where $p = P/D_x$ and $d = D/D_x$. By measuring $p = P/D_x$ and $d = D/D_x$ in various samples (or in different parts of the same sample), we obtain graph of (3b) drawn in the plane of the variables $p = P/D_x$ and $d = D/D_x$ in the form of a straight line whose slope relative to axis p allows the determination of the age $t-t_0$. In studying the evolution and age of the solar system and the Universe as a whole, a combination of chronometers of various types is used. Measurement of the isotopic relationships in stars is carried out with using the radiation spectra of corresponding atoms.

2. What Was not Taken into Account in the Cosmic Nuclear Chronometry until Now?

A. If we start the origin of time reading from the Big Bang moment, then the cosmic chronometry has obligatory to include an analysis of the formation of initial long-living radioactive nuclei. However, the estimation of the nucleosynthesis duration depends considerably on chosen models of describing the synthesis and on the involved astrophysical processes.

B. The initial quantity of the daughter nuclei formed on the previous stages of nucleosynthesis should be taken into account. After all, it is known for a long time that, in the substance of stars, the Earth, or meteorites, there is a certain starting quantity of a daughter isotope existing simultaneously with the decaying initial chronometric nuclei. This daughter isotope is not only a final stable product of the nuclear chronometer's decay, but also a possible product of other nuclear-synthesis processes or is a result of the external intrusion (such as cosmic collisions or local catastrophes). If one takes into account this factor, the estimated age of a star, the Earth, or a meteorite becomes shorter. In stars and supernovas, the so-called "neighboring nuclei" are formed apart from the parent long-living elements formed as a result of the radiation capture of neutrons and protons by nuclei in the course of nucleosynthesis of heavy elements. We choose nuclei of the parent long-living elements as initial (reference) chronometers. The neighboring nuclei are adjacent to them as regards to the atomic number [2] and cause a creation of additional channels for the formation of daughter nuclei. Amongst the neighboring nuclei, one can always find both short-living and extremely unstable nuclei formed in the "squash" of a star chaos characterizing the supernova bang. If we do not take into account these additional channels of the formation of daughter nuclei, we give a too high estimation for a geological rock under chronometric analysis.

C. Up to now, a lot of other processes remains to be unstudied, including those accompanying the supernova bang as a final stage of evolution of the first-generation stars, and those taking place after the bang, in the course of formation of a second-generation star (in particular, the Sun). Till recently, only life times of the ground states of decayed long-living nuclei had been taken into account in all the known nuclear chronometry methods. But in the course of radiation capture of nucleons taking place at final stages of nucleosynthesis of the long-living heavy elements, not only ground states are formed, but also all possible excited states of synthesized nuclei. Their existence is partially supported by both the high star temperatures and the multiple absorption acts of gamma quanta emitted by excited nuclei during their motion inside large masses, even after the cooling of the star matter emission in the course of possible scenarios of the planets and meteorites formation.

It is known that the alpha decay of excited nuclei happens much more quickly than that of nuclei sitting in their ground states. This is an immediate consequence of the Geiger—Nuttall empirical law according to which the lifetimes of alpha-radioactive nuclei are very strongly dependent of the kinetic energy of a flying-out alpha particle and, hence, of the excitation energy of a decayed nucleus. In many cases, the lifetimes of alpha-active nuclei decrease by several (4 or 5) orders (!) of magnitude if the alpha-particle energy increases by 1 or 2 MeV. Sometimes, the times of the above decays amount to 10^{-9} s and less. But, because of insuperable experimental difficulties, they practically cannot be determined; only their upper limit values are estimated which are much less (often by several orders of magnitude) as compared with the ground states. Present-day nuclear-physics data contribute to the credit of even faster gamma-transitions from the excited nuclear states into the ground ones (within $10^{-13} - 10^{-9}$ s). This is the reason that earlier formed usually a ground for the practical inexpediency of taking into account the slower processes of alpha and beta decays from the excited nuclear states. In this case, there had not been taken into account a reality of the gamma quanta absorption by the ground states of nuclei, which is preceded by their emission by excited nuclei in the course of gamma quanta propagation through large masses of matter inside stars, supernovas, planets, and meteorites. And what is more, such processes may even be multiple if the nucleus-recoil energy losses by gamma quanta during their emission/absorption are compensated by the kinetic energy of their thermal motion.

It is clear that a sufficiently full, correct, and consistent theory of decay evolution of the chronometric nuclei formed as a result of the real processes of cosmic nucleosynthesis, has to take into account:

a) evolution of the formation of these nuclei in all the possible states;

b) kinetics of all the possible gamma-transition chains (emission from a nucleus — subsequent uptake by nuclei and electrons — further emission from nuclei ...) in a substance;

c) lifetime ratios in their relation to the alpha (or beta) and gamma decay for each excited state.

The processes of emission, subsequent uptake, etc., of gamma quanta by the radioactive chronometric nuclei in a substance have been taken into account for simplest physically acceptable models in recent works of the authors (see, for example, [3, 4]) basing on the authors' generalization of Krylov-Fock quantum-mechanical theorem on disintegrating systems, which was published earlier in [5]. This account had demonstrated the possibility of an essential reduction in all the estimated time intervals characterizing the evolution of radioactive decay chains taking place in large masses of matter at various temperatures [6—8].

As an illustration, let us adduce a striking example [3, 4] of a change of the "nuclear chronometer" indication in the simplest case of the decay of long-living alpha-radioactive nuclei in two different states, the ground and first excited ones, whose parts are equal to one another at the initial moment t_0, i.e., $P_0(0) = P_1(0) = P(0)/2$, in the approximation of i) the infinitely large volume of matter; ii) the infinitely long time period $t - t_0$ (much longer than the average lifetime of the excited states, the average time of a free passage of gamma quanta through the matter, and the time of quantum oscillations due to various interference processes); iii) very short times of the gamma-decay, but not so short times $\tau_{\alpha 1}$ of the alpha decay of the excited states of radioactive nuclei as compared with $\tau_{\alpha 0}$ times of the ground states (or, more exactly, $\tau_{\alpha 1} \sim \tau_{\alpha 0}/N$ with N being the number of links in the chain of gamma emissions with subsequent uptakes); and iv) not very low temperatures (under which the gamma quanta energy losses spent for the recoil of nuclei emitting/absorbing the gamma quanta, are compensated by kinetic energy of the thermal motion of nuclei). In this case, instead of formula (3) with $P(0) = P_0(0) + P_1(0)$ (in which a usual supposition is made that all the excited nuclei transit, after emitting the gamma quanta, to the ground state and then experience the usual slow alpha decay), the formula

$$[P_0(0) + P_1(0)(1-q)]\{1 - \exp[-(t-t_0)\tau]\} +$$
$$+ qP_1(0) - D(t-t_0) + D(0) = 0, \qquad (4)$$

was obtained, q being an arbitrary-unit value determined by the part of gamma quanta withdrawn from the emission/absorption chains due to the scattering by nuclei and electrons. Approximate estimations of q give values between 1/2 and 1. From a simple comparison of (3) and (4), it can be seen that

a) at any moment of time $t - t_0$, the number of final nuclei $D(t - t_0)$ in (4) **is less** than in (3) by a value of $P_1(0) q \exp[-(t-t_0)\tau]$;

b) the same number of final nuclei $D(t - t_0)$ is achieved in (4) at the earlier moment of time $(t - t_0)$ than in (3); and

c) the bigger the contribution of $P_1(0)$ into sum $P_0(0) + P_1(0)$, the earlier is the moment t_0 of achievement of the same number of final nuclei $D(t - t_0)$ in (4) than in (3). In particular, if a certain residual number $D(t - t_0)$ of final nuclei in (3) corresponds to the time moment

$$(t - t_0)_{\text{usual}} = \tau(1+\alpha)\ln 2, \qquad (5)$$

where α is any small number $\ll 1$, then this final number $D(t - t_0)$ in (4) with $q = 1$ corresponds to the time moment $(t - t_0)_{\text{real}} = \tau\alpha$, i.e., $\ll \tau$. In other words, the billions of years obtained using the usual technique of nuclear chronometry may correspond to a much lesser number of years (about several thousands) on the scale of middle lifetimes of the chronometric nuclei. It is obvious that conclusions (1)—(3) will be more persuasive if one takes into account a larger number of the excited states in the starting ensemble of decaying chronometric nuclei. In addition, it should be taken into account that, in the limit of infinite time $t - t_0 \to \infty$, the phenomena indicated in (1)—(3) vanish eventually, but this takes place within so great time intervals (about many ten and hundred billions of years) that can not be considered in the context of common estimations of the age.

D. Age values for the Universe, stars, and the Earth obtained using the long-living beta-radioactive chronometric nuclei, are considerably overestimated:

a) Although systematic studies of the dependence of beta-radioactive nuclei lifetimes on the energy of their excitation have not been carried out up to now (because of substantial experimental difficulties), there exists a high theoretical probability of a considerable diminishing of the beta-decay lifetimes with increase of the excitation energy up to the stage of release of free beta-radioactive neutrons with the half-life period of about tens of minutes.

b) Inside the depth of stars, practically all atoms are ionized, and this fact can affect essentially the half-life period of beta-radioactive nuclei.

Recently, the effect of a dramatic lifetime decrease of long-living beta-radioactive “bald” (that is, completely ionized) nuclei was revealed experimentally. In particular, the half-life period of a cosmic chronometer ^{187}Re has been decreased from $4.3\cdot 10^{10}$ years for neutral atoms to 31 years for bald nuclei, i.e., more than by 10^9 times [6]. In that work, a theoretical explanation of this effect is provided: for a completely ionized atom, the total energy Q_b^K of beta decay of a bald nucleus, if the emitted beta electron is captured onto the K shell, is described by formula

$$Q_b^K = Q - \Delta B_e^{\text{tot}}(Z+1, Z) + B_e^K(Z+1), \tag{6}$$

where $\Delta B_e^{\text{tot}}(Z+1, Z)$ denotes the difference between the total binding energies of electrons of a neutral daughter atom (with the charge number $Z+1$) and a neutral parent atom (with the charge number Z), and B_e^{tot} is the binding energy of a K-electron in the hydrogen-like daughter atom; in this case, the larger energy of the beta decay corresponds to the lesser half-life period. In accordance with (6), nuclei which are stable in a neutral atom (with $Q < 0$) can become beta active ones under compete ionization of the atom, since $\Delta B_e^{\text{tot}}(Z+1, Z) < B_e^K(Z+1)$. Thus, it was revealed experimentally [7] that nucleus ^{163}Dy, which is neutral in a stable atom ($Q = -2.565$ eV), experiences, after being completely ionized, a beta decay to a nucleus of ^{163}Ho characterized by a half-life period of 48 days. In the case of a neutral atom ^{187}Re, a small value $Q = 2.663$ eV and a small value of the beta-transition matrix element result in a great half-life period of $4.3\cdot 10^{10}$ years. At the same time, a bald atom ^{187}Re, in the case of capturing an emitted electron onto the K shell, gives a small, experimentally measured, half-life period of 31 years under much larger values of $Q_b^K = 72.97$ keV and the beta-transition matrix element. In work [6], a clear conclusion was made on the explicit necessity of revision of the existing age estimation for stars and the whole Universe.

E. It is also known that a continuous formation of excited states takes place in chronometric nuclei subjected to even a weak, but permanently acting, cosmic radiation.

From the above discussion and analysis, we can draw the following conclusion:
the methods of large-scale nuclear chronometry give only upper limits for the estimations of the age of large cosmic objects. The question of the real age of planets, stars, and the Universe still remains opened within the scientific frame, and the common estimations of about several billion years are obviously highly overestimated.

At the present time, there is no consensus in the formation theory of planets and, in particular, the Earth. Aside from the above-mentioned Big-Bang models, there exist ones describing the formation of planets as a result of the cosmic dust condensation.

If one employs models of the first kind, then, in any Earth-mass specimen, the real and daughter nuclei are genetically indistinguishable from impurities of the same types of nuclei formed in different parts of a cooled parent star fragment. Because of this, we can approximately suppose the Earth age to be equal to the sum of a parent star or supernova before the bang and the subsequent duration of Earth’s formation, which can be determined by the nuclear chronometry technique with taking into account the cosmic radiation. In this case, the initial non-zero number of daughter stable nuclei formed in the course of the preceding nucleosynthesis in stars, and all possible chains of decay of the chronometric nuclei should be taken into account. The presence of the initial non-zero number of daughter stable nuclei leads inevitably to a real reduction of the decay time that gets longer with increasing the initial number of such nuclei.

But if one deals with the models of the second kind, the origin of the cosmic dust should be taken into account from the very beginning. In a purely hypothetic approach, the cosmic dust emerged, in part, simultaneously with first stars after the Big Bang and, partially, in the course of the cooling of the microejections of stars and supernovas during their perturbations and explosions. As yet, there exists neither a consistent theory of the dust origin independent of the origin of stars, nor a consistent theory of the dust concentration and condensation into a planet. By means of the nuclear chronometry techniques, one can give only an approximate estimation of the effective age of the Earth beginning from the hypothetic middle moment of the conditional condensation of dust into a planet if the initial numbers of parent and daughter nuclei are known for this specific moment of time and if the influence of permanent cosmic radiation is taken into account and all the possible gamma-radiation/absorption chains of chronometric nuclei are considered.

The cosmic radiation induces, at least, the Earth processes of three types: (i) permanent formation of excited states of the chronometric nuclei with much lesser decay times as compared with those of the ground states; (ii) cosmic-protons-caused knocking out of alpha particles from alpha radioactive nuclei, that means acceleration of the alpha decay; (iii) permanent decrease of chronometric nuclei as a result of collisions with cosmic protons in all the possible channels of nuclear reactions running with rearrangement of the nuclei. The mentioned processes lead to a real diminution of the parent nuclei decay times.

Let us analyze the diminution of the decay time for alpha radioactive nuclei as a result of processes of the second and third type.

Supposing the cosmic-radiation flux to be constant in time and generalizing the Krylov—Fock theorem in a manner analogous to that set forth in [3—5], for a unit volume of substance consisting of chronometric nuclei, we obtain

$$L_p(t-t_0) = [1-a(t-t_0)]L(t-t_0), \tag{7}$$

where $a = j_{\text{cosm}}\sigma\nu n$ with j_{cosm} being the flux of cosmic protons (measured in $\text{cm}^{-2}\text{s}^{-1}$); σ — total section of all the reactions resulted from collisions between protons and chronometric nuclei; ν — number of all collisions of the chronometric nuclei with the reaction products resulted from the first collision of a proton with a chronometric nucleus in the medium; n — average number of chronometric nuclei the depth unit (1 cm). The decay function $L_p(t-t_0)$ includes, besides the immediate radioactive decay, all the possible types of the parent nuclei diminution caused by their collisions with cosmic protons. It is obvious that under $(t-t_0) \geq 1/a$, $L_{P\to D}(t-t_0) = 0$ and $P(t-t_0) = 0$, and Eq. (6) is valid only for $t-t_0 \leq 1/a$.

In a general case, relationship (2), certainly, becomes invalid if one takes into account the mentioned processes. But if we restrict ourselves only to the reactions $(p, p'\alpha)$ with the total section σ_D which boost the alpha decay of the chronometer with giving the same daughter nuclei, then we come to the following particular relationship

$$L_{P\to D}(t-t_0) = [1-a_D(t-t_0)]L(t-t_0), \tag{7a}$$

for which relationship (2) is true. Here, $a_D = j_{\text{cosm}}\sigma_D\nu$ and $L_{P\to D}(t-t_0)$ is a decay function that takes into account the above processes. And relationship (3b) converts into

$$p(t)[1-a_D(t-t_0)]\exp(\Gamma_0(t-t_0)/\ldots)-$$

$$-1]-d(t)+d(t_0)=0 \tag{3c}$$

From comparison between Eq. (3b) and (3c), one can see that under $t-t_0 \to 1/a_D$, the duration of decay determined by the previous method (i.e., with no taking into account the cosmic radiation) becomes very long (much longer than $\Gamma_0/\ \ldots$).

To make preliminary estimations, we have chosen $\sigma = 3\cdot 10^{-25}$ cm^2 [10, 11] (for simplicity, we neglect the elastic and inelastic scattering), ν — between 10^2 and 10^3, the average energy of protons — about 10^9 eV, the cosmic radiation flux $j_{\text{cosm}} = 0.85$ for the upper layer of the atmosphere and $j_{\text{cosm}} = 1.75 \times \times 10^{-2}$ for the sea level [10], and $n = 0.33\cdot 10^8$. Since the ν value can not be calculated exactly (its effective value is defined not only by the average energy of protons and binding energies of nucleons, clusters and fragments, but also by unknown sections of all the possible reactions for a wide range of energies), we have restricted ourselves by simplified estimations. As a result, we have obtained a between $1/2.7 \times \times 10^5$ and $1/1.5\cdot 10^8$ years. (If one supposes $\sigma_D \approx 0.1\sigma$, then values between $1/2.7\cdot 10^6$ and $1/1.5 \times \times 10^9$ years are obtained for a.) This allows making a conclusion as to validity of the assertion that, under $P(t) \to 0$, for both the limiting values of a, in all possible cases, independently of validity or invalidity of relationship (3c), the real duration of the decay is essentially less than a theoretically predicted one with no taking into account the cosmic radiation (and can achieve, with accounting for the cosmic-protons-caused reactions, values of about $3\cdot 10^5$ years even without the chronometric nuclei excitation which also boosts the alpha decay).

3. Prospects of Actual Studies in the Field of Nuclear Chronometry

I. First of all, we see the possibilities of a wider, compete, and systematic theoretical accounting for the influence of all factors leading to the excitation and decomposition of nuclei, as well as to the ionization of atoms with such nuclei and, later on, to the development of nuclear cosmic large-scale and Earth-related short-scale chronometry.

II. Because of an obvious insufficiency of the experimental material related to the excited nuclei decay through the alpha- and beta-radiation channels and as a result of spontaneous fission, it is expedient to develop, on the base of the available poor empirical observations, a computer simulation of the lacking experimental material.

In such a consideration, all the same, a question arises of what real experimental means we have now or can expect to appear in the near future, even in a purely speculative manner. Let us try to describe these in brief.

1. Immediate experiments simulating the real (cosmological) conditions of the nucleosynthesis are connected with thermonuclear explosions and, hence, they are extremely dangerous when conducted on Earth-located testing areas, and all the more are complicated, labor-consuming, and expensive if being conducted under the cosmic conditions, although such experiments are possible in principle and have been conducted, in due time, within the frame of military programs of the USA. At present, they can be expediently combined with the studies conducted within the frame of the program of protection of our planet from its collision with an asteroid accepted in 1996 in the USA.

2. Another, even more promising (because of its being closer to the reality) experimental possibility can be connected with successes achieved in the engineering of high-current proton and electron accelerators.

3. To study the specific features of decays, there can be proposed a series of reactions initiated by electrons, protons, alpha particles, and alpha-cluster nuclei, and leading to the formation of classical isotopes of heavy alpha- and beta-radioactive chronometric nuclei and their “neighbors” in the ground and excited states which can be investigated in nuclear-physics experiments with the employment of the accelerators of heavy ions. In this case, it is interesting to carry out investigations below the Coulomb threshold the conditions of strong plasma screening and low energies of interacting charged particles (something like the cold thermonuclear synthesis).

4. The present-day state of astrophysical investigations, including the employment of the space-based observation systems and means of cosmic monitoring, allows the organization of a permanent monitoring of star objects and the in-time detection of the initial moment of a supernova blast in the course of detailed investigation of an object in various wavelength bands.

5. It seems to be promising to investigate the decay paramerers of the anomalously situated excited states of nuclei, as in the case, for example, of state (3.5 ± 1.0) eV of ^{229}Th nucleus, since, on the background of the wide-spread excitation levels (from low to high values), the studied regularities can be revealed more exactly in an experimental manner and the adequacy of related theoretical models verified.

6. Experiments involving high-power laser beams (including X-ray lasers) are also of interest.

Conclusion

A further development of theoretical and experimental studies of the external factors, which affect really and explicitly the processes of radioactive transformations, is of fundamental and applied interest for both the astrophysics and the further deeper, understanding and development of nuclear chronometry. This work allows making the following conclusions:

1. Studies in the field of nuclear, plasma-related and atomic processes taking place at the stages of creation, formation, and existence of the substance in stars, the Sun, the Earth and other cosmic objects make wider our possibilities in the application of nuclear chronometry for a real determination of absolute age values of the objects of nature.

2. The present-day theory of nucleosynthesis has to be formulated more exactly on the basis of analysis of all the known alternative mechanisms and paths of formation and decay of nuclei.

3. Taking into account in the nuclear chronometry techniques of all the possible chains of nuclei decay from excited and ionized states should lead to the revision of the existing age estimations for geological strata of the Earth to the side of a diminution by several orders of magnitude.

4. And, of course, there remains a number of unresolved and insufficiently resolved problems connected with the cosmic processes evolved from the

initial moment of the Big-Bang up to the formation of second-generation stars and affecting essentially the processes of nucleosynthesis.

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ЩО ГОВОРИТЬ ЯДЕРНА ХРОНОМЕТРІЯ ПРО ВІК ЗІРОК І ЗЕМЛІ?

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Резюме

Розглянуто фактори, які чинять суттєвий вплив на результати вимірювань ефективної тривалості розпаду великих мас речовини, що містить довгоживучі радіоактивні ядра-хронометри, які до цього часу, практично, не брали до уваги. Для конкретних моделей взаємодії космічних протонів з ядрами-хронометрами вперше аналітично і чисельно розглянуто внесок процесів вибивання альфа-частинок у зменшення ефективного періоду піврозпаду ядер-хронометрів на поверхні Землі. Отримано результати, що свідчать про те, що вік Землі може бути на кілька порядків меншим, ніж очікувалося раніше.