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No evidence for a decrease of nuclear decay rates with increasing heliocentric distance based on radiochronology of meteorites

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ABSTRACT

It has been argued that the decay rates of several radioactive nuclides are slightly lower at Earth's aphelion than at perihelion, and that this effect might depend on heliocentric distance. It might then be expected that nuclear decay rates be considerably lower at larger distances from the sun, e.g., in the asteroid belt at 2–3 AU from where most meteorites originate. If so, ages of meteorites obtained by analyses of radioactive nuclides and their stable daughter isotopes might be in error, since these ages are based on decay rates determined on Earth. Here we evaluate whether the large data base on nuclear cosmochronology offers any hint for discrepancies which might be due to radially variable decay rates. Chlorine-36 ($t_{1/2}$ = 301,000 a) is produced in meteorites by interactions with cosmic rays and is the nuclide for which a decay rate dependence from heliocentric distance has been proposed, which, in principle, can be tested with our approach and the current data base. We show that compilations of ^{36}Cl concentrations measured in meteorites offer no support for a spatially variable ^{36}Cl decay rate. For very short-lived cosmic-ray produced radionuclides (half-lives < 10–100 days), the concentration should be different for meteorites hitting the Earth on the incoming vs. outgoing part of their orbit. However, the current data base of very short-lived radionuclides in freshly fallen meteorites is far from sufficient to deduce solid constraints. Constraints on the age of the Earth and the oldest meteorite phases obtained by the U–Pb dating technique give no hints for radially variable decay rates of the α-decaying nuclides ^{235}U or ^{238}U. Similarly, some of the oldest phases in meteorites have U–Pb ages whose differences agree almost perfectly with respective age differences obtained with "short-lived" radionuclides present in the early solar system, again indicating no variability of uranium decay rates in different meteorite parent bodies in the asteroid belt. Moreover, the oldest U–Pb ages of meteorites agree with the main-sequence age of the sun derived from helioseismology within the formal ~1% uncertainty of the latter. Meteorite ages also provide no evidence for a decrease of decay rates with heliocentric distance for nuclides such as ^{87}Rb (decay mode β^-) ^{40}K (β^- and electron capture), and ^{147}Sm (α).

1. Introduction

Small unexpected periodic variations in the decay rates of some radioactive nuclides were first reported in 1986 by Alburger et al. [1]. More recent similar results are reviewed by Fischbach et al. [2], with updates, e.g., by Jenkins et al. [3]. The most prominent period observed is one year, which has led to suggestions that the sun may influence the decay rates of (at least some) radioactive nuclides [c.f. 2]. The annual periodicity has been proposed to be caused by the variable distance of the Earth from the sun (with maximum decay rates observed when the Earth was near perihelion) and some unknown physics, e.g., fields or particles emanating from the sun that might influence either the experimental apparatus or indeed the decay rates of nuclides [2]. Evaluations of whether the observed annual periodicities might instead be caused by seasonal effects like temperature or pressure fluctuations in the laboratories or other climatic effects have often come to a negative conclusion [e.g., 3]. Hence we are faced with the possibility that some nuclear decay rates may vary to a measurable degree between the perihelion (0.983 AU) and aphelion (1.017 AU) of the Earth's orbit. For ^{36}Cl the reported variability is about 1% [3], which corresponds to about one third of the relative difference between Earth's perihelion and aphelion distances. If decay rate variations would be proportional to the inverse or the inverse square of the heliocentric distance, as is envisaged in many of these studies

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[3], then decay rates might vary quite dramatically between the innermost solar system and further away from the sun. While some reports point out that only beta-decaying nuclides show variable decay rates with an annual period [4], others consider also the possibility of a variable decay rate of the α-decaying isotopes ^{226}Ra and ^{222}Rn [2,3]).

An attempt to extend the observational data base beyond the variations of Earth's orbit by analyzing decays of ^{238}Pu from radioisotope batteries carried by the Cassini spacecraft yielded a negative result for heliocentric distances between 0.7 and 1.6 AU [5]. Other studies of spacecraft radioisotope batteries have come to inconclusive results [6,7]. There is, however, a very wide body of evidence on radioactive decay rates as a function of heliocentric distance, which, to our knowledge, has not yet been considered in this context. These are concentrations of radioactive nuclides and their daughter isotopes in rocks, which are widely used to date ages of meteorites and samples from Mars, the Moon and Earth. The semi-major axes of the parent bodies of these samples cover a range between 1 AU and perhaps 3 AU (the outer edge of the main asteroid belt) or even more. It is the purpose of this contribution to raise the awareness of the decay counting community to these constraints. Spatially variable decay rates of crucial nuclides would shake the very foundations of solar system chronology. However, as we will show below, the general picture of the chronological evolution of the early solar system that evolved over the last few decades – based on the tacit assumption of spatially and temporally constant decay rates – is remarkably self-consistent. The data do not indicate radially variable decay rates in particular for the alpha-decaying nuclides ^{235}U and ^{238}U, but neither for nuclides such as ^{40}K (β^-, electron capture), ^{87}Rb (β^-), and ^{147}Sm (α). We also discuss ^{176}Lu, for which an apparent discrepancy in the decay rates in meteorites and terrestrial samples, respectively, has been reported. If governed by the distance from the sun, this presumed decay rate variation would, however, run opposite in sign to the variations claimed for ^{36}Cl etc., and another explanation for ^{176}Lu seems more likely. We also discuss the possibility of testing the hypothesis of spatially variable decay rates using cosmic-ray produced nuclides in meteorites. We show that such a test is possible, in principle, for at least some of the radionuclides with proposed decay rate variation, but also that the database of meteorites with known orbits is at present not yet large enough for this purpose.

2. Key reports on radially variable nuclide decay rates and their possible consequences for geo- and cosmochronology

Alburger et al. 1986 measured the half-life of ^{32}Si (β^- decay) by counting over 4 years the decays of its daughter ^{32}P in a ^{32}Si–^{32}P sample at the Brookhaven National Laboratory (BNL). The detector stability was monitored by alternately counting a ^{36}Cl (β^-) standard. They noted an annual periodicity of the ^{32}Si/^{36}Cl ratio (corrected for decay of ^{32}Si), which they thought to likely arise from seasonal effects as humidity or temperature changes. Jenkins et al. [8] compared these data with a similar long term data-set including the ^{226}Ra (α) activity obtained at the Physikalisch-Technische Bundesanstalt in Germany which also showed annual fluctuations [9]. The fluctuations in the two experiments strongly correlated in time, which led Jenkins et al. [8] to ask whether the decay rates of ^{32}Si and ^{226}Ra themselves might vary with the Earth – sun distance. Jenkins et al. [3] further analyzed long-term ^{36}Cl counting data obtained at the Ohio State University Research Reactor and again found an annual periodicity. They considered it to be unlikely that the observed periodicity could be explained by periodic variations of detector efficiency or background radiation and concluded that the ^{36}Cl data are further evidence for a solar influence on nuclear decay rates. Fischbach et al. [1] and Jenkins et al. [2] list several additional observations suggesting a possible influence of the sun on nuclear decay rates. Other studies, in contrast, did not find evidence for a correlation of the decay rates of various nuclides with the Earth – sun distance ([10] for ^{22}Na, ^{44}Ti, ^{108}Ag^{m}, ^{121}Sn^{m}, ^{133}Ba and ^{241}Am; [11] for ^{137}Cs).

Jenkins et al. [8] found amplitudes of roughly 2‰ in the activity ratio ^{32}Si/^{36}Cl in the BNL data of Alburger et al. [1], with count rates in northern-hemisphere winter (when the sun is near perihelion) being larger than in northern summer. In these experiments, ^{36}Cl had been used to monitor detector stability. However, the Ohio State ^{36}Cl data [3] display themselves an amplitude of about 1% between summer and winter, northern winter rates again being higher. The Ohio State and the BNL data together would then suggest that the ^{32}Si decay rates show a slightly larger variability than the ^{36}Cl decay rates. The annual ^{226}Ra fluctuations measured at the Physikalisch-Technische Bundesanstalt have a considerably smaller amplitude on the order of 2‰, the northern winter decay rate again being higher than the northern summer value.

Given proposed variations of decay rates between Earth's perihelion and aphelion of up to at least 1%, how much might the rates vary over much larger heliocentric distances relevant for extraterrestrial samples, if decay rate variations would indeed depend on the distance from the sun? Such an extrapolation is far from being straightforward, because no explicit possible physical explanation for the putative observed variations has been offered. They have been compared with curves displaying $1/r^2$ or $1/r$, r being the distance between Earth and Sun at a given time [2,3]. If decay rates were proportional to $1/r^2$ or $1/r$, their amplitude along Earth's orbit would be about 7% or 3.5%, respectively, i.e., some 3–7 times larger than the reported variations for ^{36}Cl and ^{32}Si. We thus assume here that the decay rates would scale with $1/r^x$. Exponent x becomes ~0.3 and 0.06 for a 1% and 2‰ change, respectively, between perihelion and aphelion. Extrapolating to 2.5 AU, this would result in an expected decrease of decay rates of about 30% and 6%, respectively, from the Earth's orbit to the approximate original orbits of meteorite samples in the asteroid belt – resulting in true ages that are 30% and 6% higher than accepted values. This is illustrated in Fig. 1. This $1/r^x$ scaling is an ad hoc assumption, yet it seems unavoidable that with any other assumed radial dependence, the small effects reported between Earth's perihelion and aphelion should translate into considerably larger effects when considerably larger differences in heliocentric distance are considered. We therefore adopt in the following discussion the two curves in Fig. 1 to illustrate the possible – perhaps drastic – consequences of variable decay rates for geo- and cosmochronology. Caveats in this discussion are that some of the radionuclides relevant for nuclear dating would need to be affected to a similar extent as we extrapolated above for ^{36}Cl and ^{32}Si and that the claimed variations of the latter nuclides would not be a rather recent or transient phenomenon in solar history.

Note also that an annual periodicity in decay rates might not only be the result of a variable distance of the Earth from the sun but could – in principle – also be caused by the periodic velocity difference of the Earth relative to the local interstellar medium (similar to what is considered in experiments aiming at the detection of dark matter). In such a case, decay rates in the outer solar system would even vary less than at 1 AU and the effect would cancel anyway over periods of years, so that our following considerations would not apply. In the next section, we will give a basic introduction to the principles of dating with radionuclides to the extent necessary to understand the later data evaluation.

3. Radionuclides in geo- and cosmochronology

Radioactive isotopes and their radiogenic daughters allow us to construct a time-line of solar system history from the formation of