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Is the weak interaction constant really constant?

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Abstract. A comparison is made of the probability of the process of two neutrino double-beta decay for ^{82}Se and ^{96}Zr in direct (counter) and geochemical experiments. The experimental data for ^{130}Te are also analyzed. It is shown that the probability is systematically lower in geochemical experiments, which characterize the probability of $\beta\beta(2\nu)$ decay a few billions years ago. In addition geochemical measurements on young minerals give lower values of $T_{1/2}(^{130}\mathrm{Te})$ as compared to measurements on old minerals. It is proposed that this could be due to a change in the weak interaction constant with time. The possibilities of new precise measurements to be performed with the aid of counters and geochemical experiments are discussed. A new geochemical experiment with ^{100}Mo is proposed.

PACS. 23.40.-s β decay; double β decay; electron and muon capture

1 Introduction

The question of the dependence of the fundamental constants on time was formulated by P. Dirac in 1937 —this is the so-called Large Number Hypothesis [1]. This question was later discussed in references [2–7]. Although Dirac's hypothesis was not confirmed in its initial form, interest in this problem gathered new strength in the 1980s, since a time dependence of the coupling constants appears in multidimensional Kaluza-Klein models [8,9] and in superstring theories [10] (see also refs. [11] and [12]). These theories are formulated for a multidimensional space, which must then be compactified to the four observable dimensions of space-time. In these theories the fundamental coupling constants are associated with the radii of additional dimensions and these additional dimensions can manifest themselves through a time dependence of the coupling constants. The radii can shrink, increase, or even oscillate. It has not been ruled out that the compactification process is continuing at present. A time dependence of the fundamental constants also arises in models with a massless dilaton, the scalar partner of the graviton [13]. Recently, a scheme with time variation of the velocity of light in vacuum, c, and the Newtonian gravitation constant G_{N} was proposed as a solution of cosmological puzzles and as a possible alternative to inflationary cosmology [14–17].

On the other hand, a clear regularity was discovered in the distribution of galaxies in the direction of the galactic north and south poles, with a characteristic scale of $128h^{-1}$ Mpc (where $h \sim 0.5$–1; h is a constant characterizing the uncertainty in the value of the Hubble constant) [18]. This periodicity can be explained by oscillations of the gravitational constant G_{N} in time [19–22]. For example, in reference [22] a model with an oscillating massive scalar field, which is cosmological "dark matter" and can be observed according to the oscillations of the gravitational constant, is studied. This model explains well the periodicity in the distribution of galaxies which was observed in reference [18]. Variations of the solar year, which were discovered in the deposits of corals and sea mollusca, can also serve as indirect evidence of a change in G_{N} with time [23]. The value of the period of these variations ($\sim 400 - 600$ million years) is closed to the values required to explain the periodicity in the distribution of the galaxies.

In addition, recently some indication was found that the fine structure constant α was smaller at earlier epochs, $-\Delta\alpha/\alpha = (-1.9 \pm 0.5) \cdot 10^{-5}$ for redshifts $z > 1$ [24]. But, as was mentioned in that paper, further work is required to explore possible systematic errors in the data.

So, one can conclude that there are theoretical and experimental motivations to search for time variations in the fundamental constants.

2 Present limit on the weak interaction constant time variation

Modern limits on the possible variations of different fundamental constants with time can be found in refs. [20–29]. For example, the strictest limits for the weak interaction constant were obtained from an analysis of the operation

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of the natural nuclear reactor in Oklo[1]: $\mid \Delta G_{\rm F} \mid /G_{\rm F} < 0.02$ (where $\Delta G_{\rm F} = G_{\rm F}^{\rm Oklo} - G_{\rm F}^{\rm now}$) or $\mid \dot{G}_{\rm F}/G_{\rm F} \mid < 10^{-11}$ $\rm y^{-1}$ [31]. This value exceeds the limits obtained earlier from an analysis of nucleosynthesis processes ($\mid \Delta G_{\rm F} \mid /G_{\rm F} < 0.06$) [33] and analysis of the beta decay of ^{40}K ($\mid \dot{G}_{\rm F}/G_{\rm F} \mid < 10^{-10}$ $\rm y^{-1}$) [34]. However, it should be kept in mind that these limits were obtained under the assumption that all the other constants are constant, which makes estimates of this kind less reliable. It has not been ruled out that variations of the constants are interrelated and the effect due to a change in the constant can be compensated by a change in another constant.

3 $\beta\beta$-decay and time variation of $G_{\rm F}$

Double-beta decay is of interest in itself with respect to the problem of the change in the fundamental constants with time. The probability of ordinary beta decay is proportional to $G_{\rm F}^2$, while the probability of double-beta decay goes as $\sim G_{\rm F}^4$ (since $\beta\beta$-decay is of second order in the weak interaction); $G_{\rm F}$ is the Fermi constant. For this reason, if, for example, in ordinary β-decay the effect due to a change in $G_{\rm F}$ in time is compensated by a change in other fundamental constants, then this effect could still come through in $\beta\beta$-decay. Therefore the study of the time dependence of the rate of $\beta\beta$-decay can give additional (and possibly unique) information about the possible change in $G_{\rm F}$ with time. We recall in this connection that the age of minerals and meteorites is determined by radioisotopic methods (β- and α-decay). For this reason, when attempts are made to observe a time dependence of the rate of β-decay of ^{40}K, for example, then the change in $G_{\rm F}$ can be masked by incorrect dating of the sample under study.

4 Comparison of "present" and "past" rate of $\beta\beta$-decay for ^{82}Se, ^{96}Zr and ^{130}Te

Let us compare the rate of $\beta\beta$-decay obtained in modern counter experiments to the rate of the same process obtained in geochemical experiments, which carry information about the rate of $\beta\beta$-decay in the past. Geochemical experiments are based on the separation of the products of $\beta\beta$-decay from ancient minerals followed by isotopic analysis of the products. The observation of an excess quantity of daughter isotope attests to the presence of $\beta\beta$-decay of the initial isotope and makes it possible to determine its half-life. Minerals containing tellurium, selenium, and zirconium have been investigated and the half-lives of ^{130}Te, ^{128}Te, ^{82}Se, and ^{96}Zr have been measured. Since the age of the minerals investigated ranged from ~ 28 million years up to 4.5 billion years, it is possible in principle to extract from geochemical experiments information about the values of $G_{\rm F}$ in the past —right back to the time when the solar system formed (4.5 billion years ago). If the value of $G_{\rm F}$ oscillates with time, then these oscillations can be observed.

Let us examine systematically all the existing experimental data.

1. ^{82}Se. The most accurate present-day value of the half-life of ^{82}Se with respect to the $\beta\beta(2\nu)$ channel was obtained with the NEMO-2 track detector [35]: $T_{1/2} = [0.83 \pm 0.10(\rm stat) \pm 0.07(\rm syst)] \cdot 10^{20}$ y. The following most precise values were obtained in geochemical experiments: $T_{1/2} = (1.30 \pm 0.05) \cdot 10^{20}$ y [36] (the average value for 17 independent measurements; the age of the samples ranged from 80 million years up to 4.5 billion years) and $T_{1/2} = (1.2 \pm 0.1) \cdot 10^{20}$ y [37] (the age of the sample ~ 1 billion years). Comparing these results shows that the present-day value of the half-life ^{82}Se is different from the half-life in the past (this effect is at the level $\geq 3\sigma$). If this is due to a change in the value of the weak-interaction constant, then $\Delta G_{\rm F}/G_{\rm F} \approx -0.1$, and with the errors taken into account the possible range of values is approximately $-(0.02 - 0.2)$[2]. It is interesting to note that the only experiment with a meteorite (age ~ 4.5 billion years) gave the following value of the half-life: $T_{1/2} = (1.03^{+0.33}_{-0.42}) \cdot 10^{20}$ y [38]. This value is identical, within the error limits, to the present-day value by $\sim 50\%$. If $G_{\rm F}$ does not change in time linearly but rather oscillates, then for a fortuitous value of the period of the oscillations, the values of $G_{\rm F}$ at present could coincide exactly with the value 4.5 billion years ago, for example.

The accuracy of the present-day values of the half-life of ^{82}Se can be increased to several percent, and such measurements will be performed on the NEMO-3 track detector [39]. The basic problem is to increase the accuracy of the results of geochemical measurements. Modern mass spectrometry makes it possible to perform such measurements with an accuracy of several percent (see, for example, [40]). The age of the samples is also determined, as a rule, with an accuracy of several percent. The main uncertainty in geochemical experiments with ^{82}Se is due to the determination of the effective "retention" age of daughter ^{82}Kr in minerals. To solve this problem it is necessary to pick samples which have a well-known geological history and for which the retention age of ^{82}Kr can be accurately determined.

2. ^{96}Zr. The present-day value of the half-life of ^{96}Zr with respect to the $\beta\beta(2\nu)$ channel was recently measured with the NEMO-2 detector and equals $T_{1/2} = [2.1^{+0.8(\rm stat)}_{-0.4(\rm stat)} \pm 0.2(\rm syst)] \cdot 10^{19}$ y [41]. A geochemical experiment (the age of the sample was 1.7 billion years) gave the value $T_{1/2} = (3.9 \pm 0.9) \cdot 10^{19}$ y [42]. One can see that the present-

[1] The first analysis of the Oklo data for a possible change in the fundamental constants with time was done in reference [32].

[2] These values were obtained using the dependence $T_{1/2} \sim G_{\rm F}^{-4}$. However, if the dependence $\sim G_{\rm F}^{-2}$ is used, which takes into account the possible "incorrect" dating of the sample, then the corresponding values will be approximately $\sim -(0.04 - 0.4)$. We note, however, that in the case of oscillations the interpretation of the experimental data becomes much more complicated and depends on the value of the period of the oscillations.

day value of the half-life is approximately half of the value in the past. However, the errors in both experiments are quite large and it cannot be concluded unequivocally that the half-lives are different[3]. New measurements with ^{96}Zr, in which the half-life will be determined with an accuracy of 10% using the NEMO-3 detector [39], and new geochemical measurements with good accuracy ($\sim 10\%$) could clarify this situation. We note that in the present case of the $\beta\beta$-decay of ^{96}Zr it is a metal (^{96}Mo) that forms and not a gas, as in the $\beta\beta$-decay of ^{130}Te, ^{128}Te and ^{82}Se (^{130}Xe, ^{128}Xe and ^{82}Kr, respectively). This gives hope that the problems involved in determining the retention age of the decay products will be considerably smaller in this case.

3. ^{130}Te, ^{128}Te. Only data from geochemical measurements are available for these isotopes. Although the ratio of the half-lives of these isotopes has been determined to a high degree of accuracy ($\sim 3\%$) [40], the absolute values of $T_{1/2}$ differ substantially in different experiments. One group of authors [37,45–47] presents the values $T_{1/2} \approx 0.8 \cdot 10^{21}$ y for ^{130}Te and $T_{1/2} \approx 2 \cdot 10^{24}$ y for ^{128}Te, while another group gives $(2.55 \pm 0.2) \cdot 10^{21}$ y [36] and $(2.7 \pm 0.1) \cdot 10^{21}$ y [40] for ^{130}Te and $(7.7 \pm 0.4) \cdot 10^{24}$ y [40] for ^{128}Te. On closer examination one can conclude that, as a rule, experiments with "young" minerals (< 100 million years) give $\sim$ (0.7–0.9) $\cdot 10^{21}$ y for ^{130}Te, whereas experiments on "old" (≥ 1 billion years) minerals give $\sim$ (2.5–2.7) $\cdot 10^{21}$ y. It is interesting to note that even in the very carefully performed study in ref. [40] a half-life $\sim 0.9 \cdot 10^{21}$ y was obtained for samples with an age of 28 million years (see Table VI in ref.[40]), though the final result ($(2.7 \pm 0.1) \cdot 10^{21}$ y) was obtained by studying samples whose age was > 1 billion years.

Probably, this is mainly due to an incorrect estimate of the retention age of xenon in old samples (see the discussion in ref. [46]), but it cannot be ruled out that, to some extent, this could be also due to a change in $G_{\rm F}$. In this connection it is very important to perform precise measurements of the present-day value of the half-life of ^{130}Te. Such measurements will be performed in the near future in an experiment with low-temperature TeO_2 detectors [48] and with the NEMO-3 track detector [39]. It is also obvious that new geochemical measurements with samples of different age and accuracy $\sim 10\%$ are required. This problem can be solved only by careful selection of the experimental samples (with well-known history and with a possibility of determining accurately the xenon retention age) and by using highly sensitive mass spectrometry. Unfortunately, a direct measurement of the half-life of ^{128}Te is virtually impossible because it is too long.

[3] Note that in geochemical experiments the sum decay rate of the ^{96}Zr-^{96}Mo transition is measured. Present limits on the single-beta decay of ^{96}Zr ($T_{1/2} > 3.8 \cdot 10^{19}$ y [43]) and the $\beta\beta2\nu$ decay to the 0^+ excited state of ^{96}Mo ($T_{1/2} > 6.8 \cdot 10^{19}$ y [44]) cannot exclude the possibility that these processes contribute to the ^{96}Zr-^{96}Mo transition. If this is the case, the real half-life value for the $\beta\beta2\nu$ decay of ^{96}Zr from geochemical experiments can be even higher than presented in [42].

In summary, the analysis has shown the following:

1. A discrepancy exists between the values of the half-life of ^{82}Se which were obtained in modern counterexperiments and in geochemical measurements.

2. The ^{96}Zr data show the same tendency as the ^{82}Se data —the present-day value of $T_{1/2}$ is less than the value obtained in geochemical measurements. However, the measurement errors make it impossible to conclude unequivocally that the half-lives are unequal.

3. Geochemical measurements on young minerals give lower values of $T_{1/2}(^{130}\text{Te})$ as compared to measurements on old minerals. That is the same tendency as for ^{82}Se and ^{96}Zr.

These discrepancies can all be explained (at least partially) by a change in $G_{\rm F}$ with time. If this is indeed the case, then this will have the most serious consequences for modern physics and astrophysics. But, this is why it is necessary to confirm (or refute) reliably the reality of these discrepancies. This can be done only by performing new and more accurate measurements. We propose the following:

- precise laboratory measurements of the present-day values of the $\beta\beta2\nu$-decay half-lives of ^{82}Se, ^{96}Zr and ^{130}Te should be performed;

- new, precise measurements of the half-lives of ^{82}Se, ^{96}Zr and ^{130}Te in geochemical experiments should be performed; for each isotope it is desirable to perform measurements with minerals of different age in order to follow the character of the dependence of $G_{\rm F}$ on the time;

- the possibility of performing geochemical experiments with ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{110}Pd, ^{150}Nd and ^{76}Ge should be investigated, and if possible such measurements should be performed; this will make it possible to enlarge the range of isotopes investigated, since the half-lives of ^{100}Mo, ^{116}Cd, ^{150}Nd and ^{76}Ge have already been measured in direct (counter) experiments [49-52], while the half-lives of ^{124}Sn and ^{110}Pd can be measured in the near future.

For all isotopes listed above, the products of $\beta\beta$- decay are not gases, so that the problems related to their being retained in the minerals studied can be expected to be much smaller. The best candidate is ^{100}Mo because of the following reasons: 1) maximal $\beta\beta$-decay rate; 2) high concentration in natural Mo (9.6%) and 3) ^{100}Ru (not gas!) as final nucleus. One can see that conditions of geochemical experiments with ^{100}Mo will be approximately 10 times better than in the experiment with ^{96}Zr which was already done [42].

5 Concluding remarks

We demonstrated that there are discrepancies between results of direct and geochemical $\beta\beta$-decay experiments in ^{82}Se and ^{96}Zr and between results for ^{130}Te with "young" and "old" minerals of Te. One of the possible explanation of these discrepancies could be the time variation of $G_{\rm F}$. To check this hypothesis new direct and geochemical experiments are proposed.

In fact, $G_{\rm F}$ is not a "real" fundamental constant. Following, for example, ref. [53] one can write the connection

between the true gauge coupling constant of electroweak interaction g and $G_{\rm F} : g^2/8m_{\rm W}^2 = G_{\rm F}/\sqrt{2}$ (where $m_{\rm W}$ is a mass of W boson). And using expression $m_{\rm W}^2 = g^2\eta^2/4$ (where η is the vacuum expectation value of the Higgs field) one can obtain $\eta \sim 1/\sqrt{G_{\rm F}}$. It means that if $G_{\rm F}$ is increasing with time then η is decreasing.

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