Possible Evidence of Time Variation of Weak Interaction Constant from Double Beta Decay Experiments

A.S. Barabash (barabash@vxitep.itep.ru)
Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia

Abstract. A comparison is made of the probability of the process of two neutrino double beta decay for $^{82}$Se in direct (counter) and geochemical experiments. 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. The experimental data for $^{130}$Te are also analyzed. It is shown that geochemical measurements on young minerals give lower values of $T_{1/2}(^{130}\text{Te})$ and $T_{1/2}(^{82}\text{Se})$ 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. Possibilities of new, precise measurements be performed with the aid of counters and geochemical experiments are discussed.

Keywords: double beta decay, time variation of fundamental constants, Fermi constant, vacuum expectation value of Higgs field.

1. Introduction

The question of the dependence of the fundamental constants on time was formulated by P. Dirac in 1937 - this is so-called Large Number Hypothesis [1]. Although Dirac's hypothesis was not confirmed in its initial form, interest in this problem gathered new strength in the 1980s-1990s, since a time dependence of the coupling constants appears in multidimensional Kaluza-Klein-like models [2, 3] and in superstring theories [4, 5, 6, 7]. Recently 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 possible alternative to inflationary cosmology [8, 9, 10, 11].

On the other hand, it was found some indication that the fine structure constant $\alpha$ was smaller at earlier epochs, $\Delta \alpha/\alpha = (-0.72 \pm 0.18) \cdot 10^{-5}$ for redshifts $0.5 < z < 3.5$ [12]. But 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.

In this report I present the situation in double beta decay where dependence of double beta decay rate with time was recently indicated [13, 14].
2. Present limit on weak interaction constant time variation

Modern limits on the possible variations of different fundamental constants with time can be found in review [15]. For example, the strictest limits for the weak interaction constant were obtained from an analysis of the operation of the natural nuclear reactor in Oklo \cite{1}:

\[ |\Delta G_F / G_F| < 0.02 \] (where \( \Delta G_F = G_F^{\text{Oklo}} - G_F^{\text{now}} \)) or \( |\dot{G}_F / G_F| < 10^{-11} \text{ y}^{-1} \) \cite{17}. This value exceeds the limits obtained earlier from an analysis of nucleosynthesis processes (\( |\Delta G_F / G_F| < 0.06 \)) \cite{18} and analysis of the beta decay of \(^{40}\text{K}\) (\( |\dot{G}_F / G_F| < 10^{-10} \text{ y}^{-1} \)) \cite{19}. 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 \(G_F\)

Double beta decay is of interest in itself in the problem of the change in the fundamental constants with time. The probability of ordinary beta decay is proportional to \(G_F^2\), while the probability of double beta decay goes as \(\sim G_F^4\) (since \(\beta\beta\)-decay is of second order in the weak interaction); \(G_F\) is the Fermi constant. For this reason, if, for example, in ordinary \(\beta\) decay the effect due to a change in \(G_F\) 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 \(G_F\) with time. We recall in this connection that the age of minerals and meteorites is determined by radioisotopic methods (\(\beta\)- and \(\alpha\)-decay). For this reason, when attempts are made to observe a time dependence of the rate of \(\beta\)-decay of \(^{40}\text{K}\), for example, then the change in \(G_F\) can be masked by incorrect dating of the sample under study.

4. Comparison of "present" and "past" rate of \(\beta\beta\)-decay for \(^{82}\text{Se}\) and \(^{130}\text{Te}\)

Let us compare the rate of \(\beta\beta\)-decay obtained in modern counter experiments to the rate of the same process obtained in geochemical

\^1 The first analysis of the Oklo data for a possible change in the fundamental constants with time was done in Ref. \cite{14}
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 and selenium have been investigated and the half-lives of $^{130}$Te, $^{128}$Te and $^{82}$Se have been measured. Since the age of the minerals investigated ranged from $\sim 28$ million years up to 4.5 billion years, it is possible in principle to extract from geochemical experiments information about the values of $G_F$ in the past – right back to the time when the solar system formed (4.5 billion years ago). If the value of $G_F$ 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 \[20\]: $T_{1/2} = [0.83 \pm 0.10(stat) \pm 0.07(syst)] \cdot 10^{20}$ y. The following most precise value was obtained in geochemical experiments: $T_{1/2} = (1.30 \pm 0.05) \cdot 10^{20}$ y \[21\] (the average value for 17 independent measurements; the age of the samples ranged from 80 million years up to 4.5 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 $\Delta G_F/G_F \approx -0.1$, and with the errors taken into account the possible range of values is approximately $-0.02$ to $-0.2$. 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.

Let us now to analyse all published results by this time (including results obtained after 1986) and results presented in \[21\], mainly, results from \[22, 23, 24, 21, 25, 26\]. The results were analysed in three time intervals, $t < 0.1 \cdot 10^9$ y, $0.17 \cdot 10^9 < t < 0.33 \cdot 10^9$ y and $1 \cdot 10^9 < t < 2 \cdot 10^9$ y. The following values were obtained: $T_{1/2} = (0.8 \pm 0.15) \cdot 10^{20}$ y, $T_{1/2} = (1.32 \pm 0.06) \cdot 10^{20}$ y and $T_{1/2} = (1.28 \pm 0.07) \cdot 10^{20}$ y, respectively. One can see dependence the half-life value with age of minerals. It means that probability of double beta decay rate of $^{82}$Se now is $\sim 50-70\%$ higher than in the past.

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 ($\sim 3\%$) \[28\], the absolute values of $T_{1/2}$ differ substantially in different experiments. One group of authors \[24, 29, 30, 31\] presents the values $T_{1/2} \approx 0.8 \cdot 10^{21}$
y for $^{130}\text{Te}$ and $T_{1/2} \approx 2 \cdot 10^{24}$ y for $^{128}\text{Te}$, while another group \cite{21, 28} gives $\sim (2.55 - 2.7) \cdot 10^{21}$ y and $(7.7 \pm 0.4) \cdot 10^{24}$ y, respectively. 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 $^{130}\text{Te}$, whereas experiments on "old" ($\geq 1$ billion years) minerals give $\sim (2.5 - 2.7) \cdot 10^{21}$ y.

Let us now again analyse all published results for $^{130}\text{Te}$, mainly, results from \cite{32, 29, 22, 33, 34, 35, 36, 37, 38, 39, 40, 25, 26, 28, 31}. The results were analysed in two time intervals, $t < 0.1 \cdot 10^9$ y and $1 \cdot 10^9 < t < 2.75 \cdot 10^9$ y. The following average values were obtained: $T_{1/2} = (0.81 \pm 0.05) \cdot 10^{21}$ y and $T_{1/2} = (1.71 \pm 0.04) \cdot 10^{21}$ y, respectively. One can see again the dependence of half-life value on age of minerals.

In this connection it is very important to perform precise measurements of the present-day value of the half-life of $^{130}\text{Te}$ and $^{82}\text{Se}$. Such measurements will be performed in the near future in an experiment with the NEMO-3 track detector \cite{27}. It is also obvious that new geochemical measurements with samples of different age and accuracy $\sim 10\%$ are required. Modern mass spectrometry makes it possible to perform such measurements with an accuracy of several percent (see, for example, \cite{28}). The age of the samples is also determined, as a rule, with an accuracy of several percent. The main uncertainty in geochemical experiments with $^{82}\text{Se}$ and $^{130}\text{Te}$ is due to the determination of the effective "retention" age of daughters $^{82}\text{Kr}$ and $^{130}\text{Xe}$ 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 $^{82}\text{Kr}$ and $^{130}\text{Xe}$ can be accurately determined.

In summary, analysis has shown the following:

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

2. Geochemical measurements on young minerals give lower values of $T_{1/2}(^{82}\text{Se})$ as compared to measurements on old minerals.

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

These discrepancies can all be explained (at least partially) by a change in $G_F$ 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:

\footnote{Uncorrected value from \cite{40} was used}
precise laboratory measurements of the present-day values of the $\beta\beta$-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 $G_F$ 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 [11, 12, 13, 14], while the half-lives of $^{124}$Sn and $^{110}$Pd can be measured in the near future.

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.

5. Concluding remarks

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

In fact, $G_F$ is not a "real" fundamental constant. Following, for example, ref. [15] one can obtain that $\eta \sim 1/\sqrt{G_F}$ (where $\eta$ is the vacuum expectation value of the Higgs field). It means that if $G_F$ is increasing with time then $\eta$ is decreasing. Therefore mass of fermions will decrease with time too.

6. Acknowledgements

In conclusion, I wish to express my appreciation to L.B. Okun for a number of helpful remarks.

This work was supported by INTAS (grant No. 00-00362).

References

1. Dirac P.A.M.: 1937, Nature 139, p. 323.
2. Chodos A., and S. Detweiler: 1980, Phys. Rev. D 21, p. 2167.
3. Marciano W.J.: 1984, Phys. Rev. Lett. 52, p. 489.
4. Wu Y.-S., and Z.W. Wang: 1984, Phys. Rev. Lett. 52, p. 489.
5. Kolb E.W., M.J. Perry, and T.P. Walker: 1986, Phys. Rev. D 33, p. 869.
6. Griego J., and H. Vucetich: 1989, Phys. Rev. D 40, p. 1904.
7. Damour T., and A.M. Polyakov: 1994, Nucl. Phys. B 423, p. 532.
8. Albrecht A., and J. Magueijo: 1999, Phys. Rev. D 59, p. 043516.
9. Barrow J.D.: 1999, Phys. Rev. D 59, p. 043515.
10. Clayton M.A., and J.W. Moffat: 1999, Phys. Lett. B 460, p. 263.
11. Avelino P.P., and C.J.A.P. Martins: 1999, Phys. Lett. B 459, p. 468.
12. Webb J.K. et al.: 2001, Phys. Rev. Lett. 87, p. 091301.
13. Barabash A.S.: 1998, JETP Lett. 68, p. 1.
14. Barabash A.S.: 2000, Eur. Phys. J. A 8, p. 137.
15. Uzan J.-Ph: 2002, hep-ph/0205340.
16. Shlyakhter A.I.: 1976, Nature 264, p. 340.
17. Damour T., and F. Dyson: 1996, Nucl. Phys. B 480, p. 37.
18. Reeves H.: 1994, Rev. Mod. Phys. 66, p. 193.
19. Dyson F.J.: Aspects of Quantum Theory, edited by A. Salam, and E.P. Wigner, Cambridge University Press, Cambridge, 1972, p. 213.
20. Arnold R. et al.: 1998, Nucl. Phys. A 636, p. 209.
21. Kirsten T. et al.: in Proceedings of the International Symposium "Nucler Beta Decay and Neutrino, Osaka'86", edited by T. Kotani et al. World Scientific, Singapore, 1987, p. 81.
22. Kirsten T. et al.: 1967, Z. Physic Bd. 202, p. 273.
23. Kirsten T., and H.W. Muller: 1969, Earth Planet Sci. Lett. 6, p.271.
24. B. Srinivasan B. et al.: 1973, Econ. Geolog. 68, p. 252.
25. Lin W.J. et al.: 1986, Nucl. Phys. A 457, p. 285.
26. Lin W.J. et al.: 1988, Nucl. Phys. A 481, p. 477.
27. Barabash A.S. et al.: in Proceedings of the International Conference "Neutrino'96", edited by K. Enqvist et al. World Scientific, Singapore, 1997, p. 374.
28. Bernatowicz T. et al: 1993, Phys. Rev. C 47, p. 806.
29. Takaoka N., and K. Ogata: 1966, Z. Naturforsch. 21a, p. 84.
30. Manuel O.K.: in Proceedings of the International Symposium "Nucler Beta Decay and Neutrino. Osaka'86", edited by T. Kotani et al. World Scientific, Singapore, 1987, p. 71.
31. Takaoka N., Y. Motomura, and K. Nagano: 1996, Phys. Rev. C 53, p. 1557.
32. Inghram M.G., and J.H. Reynolds: 1950, Phys. Rev. 78, p. 822.
33. Kirsten T. et al.: 1967, Z. Naturforsch. 22a, p. 1783.
34. Kirsten T. et al.: 1968, Phys. Rev. Lett. 20, p. 1300.
35. Alexander E.C. et al.: 1969, Earth Planet. Sci. Lett. 5, p. 478.
36. Srinivasan B. et al.: Econ. Geolog. 67, p. 592.
37. Srinivasan B. et al.: Nucl.Chem. 34, p. 2381.
38. Hennecke E.W. et al.: 1975, Phys. Rev. C 11, p. 1378.
39. Kirsten T. et al.: 1983, Phys. Rev. Lett. 50, p. 474.; Z. Phys. C 16, p. 189.
40. Richardson J.F. et al.: 1986, Nucl. Phys. A 453, p. 26.
41. Dassie D. et al.: 1995 Phys. Rev. D 51, p. 2090.
42. Arnold R. et al.: 1996, Z. Phys. C 72, p. 239.
43. Gunther M. et al.: 1997, Phys. Rev. D 55, p. 54.
44. De Silva A. et al.: 1997, Phys. Rev. C 56, p. 2451.
45. Okun L.B.: Leptons and Quarks, Nauka, Moscow, 1990.