Chapter 7

Accelerated Decay: Theoretical Considerations

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Abstract. I discuss the possibility of variation of coupling constants and particle masses within modern physics. Quantum mechanical calculations are presented giving the decay constant for α-decay and its variation with depth of the nuclear potential well. Concrete, numerical approaches are considered for the possible variation of the Fermi constant and strong coupling constant over the history of the earth. The dependence of forbidden β-decays on the decay energies is considered as a mechanism which affects the sensitivity of the half-life to changes in coupling constants. For double β-decay data, evidence from experimental data for ^{82}Se, gathered from both geochemical and direct laboratory detection methods, is considered which indicates possible accelerated decay episodes. In addition, data from the Oklo natural reactor are considered as to whether they constrain the possible variation of half-lives.

1. Introduction

The subject of *accelerated* radioactive decay is the study of the possibility that radioisotope half-lives had smaller values earlier in history than today. This chapter will concern itself mainly with physical ideas which may serve as viable models of accelerated decay. In recent times, new understandings of mathematics and physics have enabled reasons and explanations to be given in particle physics which had not been previously possible. Attempting to take advantage of these new descriptive capabilities, we wish to consider the possibility that modern quantum theory, field theory, Kaluza-Klein theory, and string theory

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may prove relevant to the age of the earth question. Various concepts from these theories lead to possible mechanisms for changing half-lives. One of these concepts is the idea that gravitational, electromagnetic, weak nuclear, and strong nuclear forces may fit into a single theoretical framework. In field theory, a Feynman diagram is used to facilitate the construction of expressions for probabilities of various particle reaction processes. For each vertex of the Feynman diagram, a coupling constant is inserted, depending on the type of interaction taking place at that vertex. In this chapter we will advance the hypothesis that the coupling constants for the strong and possibly the weak force are actually not constants but variables. We shall point out many instances in the scientific literature where physicists have considered this as a real possibility. In order to avoid confusion about which terms we are actually describing, we shall continue to call these quantities constants even though they are being considered as variables. Because they are variables, rates of nuclear decay may vary over time and actually shrink the timescale that is indicated by isotopic abundance measurements.

Alpha decay, in modern theory, is described in terms of tunneling of a preformed α-particle out through a barrier which classical physics forbids it to cross. In a preliminary section of this chapter, we will consider this theory, plus an assumption that the strength of the nuclear force could change during Creation week, during the Flood year, or at various other points in history. We shall see that changes in the number of nodes in α-particle wavefunctions are very important in determining half-lives. If the age of the earth is measured in thousands rather than billions of years, then how does one explain the isotopic abundances of, for example, U, as found in geologic samples? If half-lives have varied over earth history, then nuclear physics must be altered in some way, and the altered theories could lead to new explanations for the isotopic abundance variations with time [*Chaffin*, 2000a,b, 2001]. We shall spend a section examining the concept of radioactive equilibrium in this light, and also a section on the Oklo natural reactor and the constraints it provides on the variations. Then some of the mathematical aspects of string theory will be discussed and the relations of diameters and shapes of compactified extra dimensions to the values of gauge coupling constants, Yukawa coupling constants, and particle masses. It will be hypothesized that the electron mass is constant and that changes in the electromagnetic force have been minimal; changes in the proton mass have been relatively small but probably not zero, whereas changes in the strong coupling constant have been large. Reasons will be given why the weak interaction coupling constant may also have changed, but not as much as the strong coupling constant. As a possible experimental support for these ideas, we will end by discussing forbidden β-decays and double β-decays.

2. Alpha-Decay and Variation of the Nuclear Force Strength

Historically, the numerical treatment of α-decay has relied on quantum mechanics and the tunneling theory [*Preston*, 1947; *Pierronne and Marquez*, 1978]. Figure 1 shows the usual scheme where the potential felt by an α-particle is modeled by a square well for the interior of the nucleus and a Coulomb repulsion outside. For heavy nuclei, the well depth appropriate for an α-particle is over 100 MeV [*Pierronne and Marquez*, 1978; *Buck et al.*, 1990, 1992]. Classically, a particle could

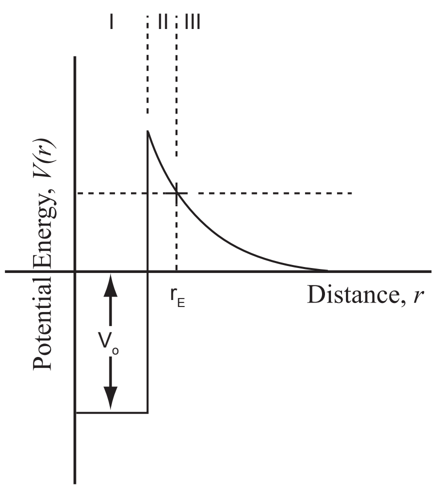


Figure 1. The square-well potential with Coulomb barrier. *V(r)* is the potential energy of the α-particle due to the nucleus, and *r* is the distance from the nuclear center.

not occupy region II of the figure. When a particle is in region II it is under the barrier and thus has a large positive potential energy. Thus it would have to have negative kinetic energy in order to have the same total energy of only a few MeV as when it escapes to infinity. However, a wave such as that used in quantum theory can leak through, even though a particle would have a negative kinetic energy for radius less than the r_E value shown in the figure.

Although the changes in physical "constants" suggested in recent physics literature are very small [*Chaffin*, 2000b], α-decay rates are very sensitive to small changes in well depths or well shapes. *Chaffin* [1994, 2003] discussed results of a numerical study, using a simple computer program, which allowed the depth of the nuclear potential well to vary. The radius of the nucleus and the depth of the potential well represent two variables which are tied to the energy of the emitted α-particle and the decay constant. In this simple model a constraint is needed, which may be taken to be the approximate constancy of radioactive halo radii [*Gentry*, 1986; *Chaffin*, 1994, 2000b; *Humphreys*, 2000; *Snelling*, 2000]. If the energy of the α-particle is held constant, then the halo radius will also be constant. Since the radius of a halo ring is slightly dependent on the dose of radiation and the size of the halo inclusions, an exact constraint on the α-particle energy cannot be maintained. For a 5 MeV change in the potential well depth, with the α-energy held exactly constant the computer program showed that the decay constant will change by only one power of ten. If the α-energy is allowed to change by 10% or so, then the decay constant changes by about 10^5. If the accelerated decay needed to explain the data is restricted to about one year or so, then a change in the decay constant of 10^9 or so may be required [*DeYoung*, 2000]. Thus these considerations seemed to indicate that a one-year episode of accelerated decay at the time of the Flood may not be enough.

To test the variability of the decay constant, the computer program mentioned above, which was a Fortran program, was rewritten using *Mathematica*, a very powerful, modern software package which facilitates numerical work of this sort. For the square well potential on the inside of the nucleus, the *Mathematica* notebook gave essentially the same answers as the earlier work. In collaboration with Gothard and Tuttle [*Chaffin et al.*, 2001], Chaffin modified the notebook to use a harmonic oscillator potential for the interior region, where the nuclear potential is felt by the α-particle. In the course of this work, it was discovered that, as the nuclear potential well depth is changed, and the nuclear radius changes slightly, it is possible to have a sudden change in the number of nodes of the real part of the α-particle's wavefunction (Figure 2). This was modeled for both the harmonic oscillator and square well potentials, with nearly the same results for either notebook.

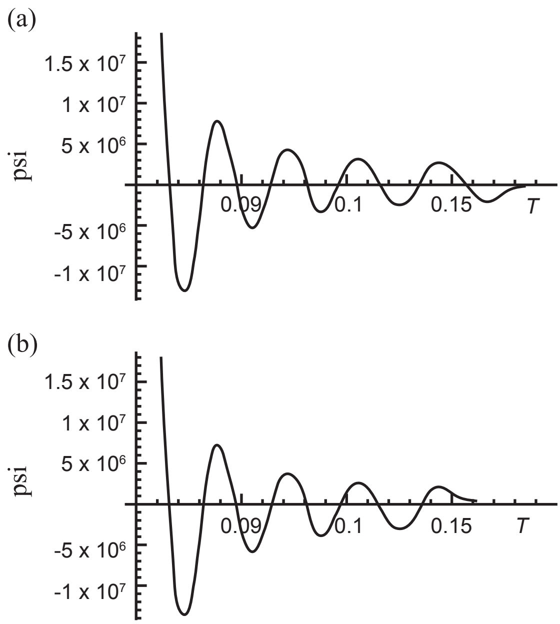


Figure 2. Sudden change in the number of nodes (zero crossings). The harmonic oscillator wavefunction for well depths of 58 MeV (a) and 54 MeV (b). The *x*-axis is the radial coordinate of the α-particle, $T=\rho/(2\eta)$, where ρ and η are defined in *Green and Lee* [1955]. Figure 2a shows the harmonic oscillator wave function for a well depth of 58 MeV. Figure 2b shows what happens when the well depth is changed to 54 MeV, without changing the α-particle energy. If one counts the number of nodes in Figure 2a, there are nine, not counting the ones at zero and infinity. For Figure 2b, there are eight nodes, a reduction by one.

The change in the number of nodes causes the probability of tunneling to change by about a factor of ten, as shown by the discontinuity in the graph of Figure 3. Tunneling probabilities depend on the size of the wavefunction at infinity. The two graphs of Figure 2a, b show the wavefunction decreasing to zero at infinity. The x-axis shows a dimensionless variable T (defined in [*Fröberg*, 1955]), whose size represents the distance from the nucleus. The graph appears to decrease to near zero for large distances from the nucleus. However, the probability of α-decay for a nucleus such as ^{238}U is very low, hence the wavefunction will have small oscillation of both its real and imaginary parts, too small to show on this scale. Figure 4 shows a plot of the real part of the wavefunction for well depth parameter of 54 MeV, produced with *Mathematica* simulations. This plot (Figure 4) shows only the wavefunction outside the nucleus, because the scale needed to be changed to show the very small oscillations found there is too small to see on Figure 2. Such very small oscillations would be typical of a nucleus which has a very long half-life.

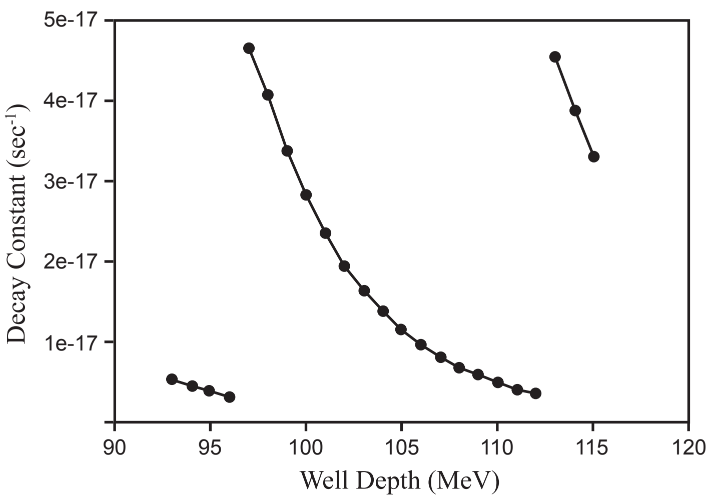


Figure 3. The decay constant versus well depth for the harmonic oscillator interior potential. The graph shows a discontinuity, which occurs when the wavefunction changes the number of nodes as the radius slowly increases.

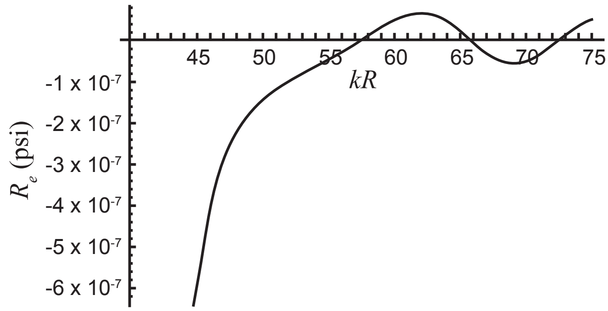


Figure 4. The real part of the Coulombic wavefunction outside the Coulomb barrier. The oscillatory behavior shows that the probability of escape is not zero for the α-particle. The *x*-axis is the dimensionless radial coordinate $\rho = kR$. The equations needed to give a precise definition of ρ are given in *Green and Lee* [1955] or *Fröberg* [1955].

The use of potentials with a sharp boundary between the interior and exterior of the nucleus is not realistic. Consequently, in collaboration with Banks [*Chaffin and Banks*, 2002], a *Mathematica* notebook was written to use the exponentially diffuse boundary square well for the interior of the nucleus. This interior potential was originally investigated in a classic work by *Green and Lee* [1955], although they did not apply it to α-decay. Figure 5 shows the potential well and the corresponding wavefunction for this case.

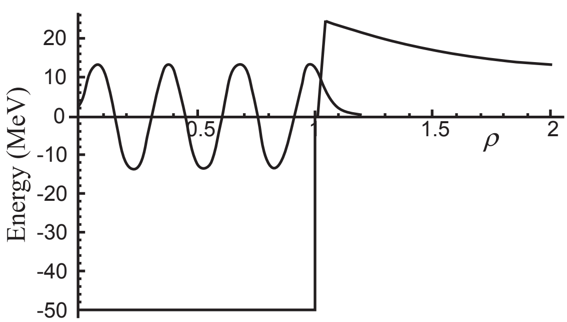


Figure 5. The exponentially diffuse boundary potential and the corresponding wavefunction. The vertical axis is energy in MeV and the horizontal axis is the radius ρ, in units where 1 is about ten fermis (one fermi is the same as one femtometer or 10^{-15} m). For the wavefunction, the vertical axis is the real part of the wavefunction scaled by a factor of ten.

The use of this potential allows the potential energy to increase gradually as the distance increases outward and the nuclear force yields to the Coulomb repulsion. The treatment is somewhat complicated, in that now the wavefunction is a spherical Bessel function in the interior of the well, whose logarithmic derivative is matched to a Bessel function of non-integral order in the changeover (or barrier) region, and then to a Coulomb wavefunction for the exterior region. The non-integral order of the wavefunction is a decimal fraction which is determined from the matching by iterative procedure [*Chaffin and Banks*, 2002]. There is now an interior radius for the changeover region, as well as an exterior radius. Either one can be varied to see what the effect is. In the case of the square well potential with sharp edges, the uncertainty in the radii of ancient radiohalos led to an uncertainty in the α-particle emission energies. For the square well potential, it was found that if the α-energy is allowed to change by 10% or so, then the decay constant changes by about 10^5. For the diffuse boundary potential, it is found that variations in the decay constant of the order of magnitude of 10^5 to 10^8 occur in some cases for a small change in the well depth parameter, when the number of nodes in the wavefunction changes. Thus this is about what we obtained for the simpler cases of the square well or harmonic oscillator well, when the α-particle energy was varied, but now the diffuse boundary allows such variations without changes in α-energy. More specifically, when the well depth was 96 MeV the *Mathematica* notebook runs showed a change from $\lambda = 2.4 \times 10^{-4}\,\mathrm{s}^{-1}$ to $7.98 \times 10^{-12}\,\mathrm{s}^{-1}$ when the number of nodes changed from thirteen to twelve.

In these calculations I have tried to use realistic values of the nuclear parameters. However, when we are considering these hypothetical changes in the nuclear force in ancient times, it is not a matter of fitting data that has been measured in a modern laboratory, but instead one must consider a range of possible parameters. Modern scattering data [*Gils and Rebel*, 1976] show that the nuclear potential in a heavy nucleus drops to zero within a distance of about two fermis. Hence the diffuseness of the nuclear surface must reflect a variation of this order of magnitude and not a bigger one.

Experimental data on α-particle and heavy ion scattering [*Wildermuth and McClure*, 1966; *Anyas-Weiss et al.*, 1974; *DeVries et al.*, 1975; *Buck*, 1976; *Davies et al.*, 1976] have long been known to validate a cluster model in which an α-particle moves in the average field provided by the rest of the nucleus. Four-nucleon transfer reactions were observed on target nuclei that are the daughters of an α-emitter. The comparison of reaction rates with the corresponding α-decay rates indicates the tendency for the four transferred particles to form a true α-particle. The data give evidence that nodes in the α-particle wavefunction do in fact exist. When the nuclear potential seen by the α-particle is represented by a square well, the effect of changing the depth of the well is to change the α-particle wavefunction. Usually this change is slight, but at certain critical values the number of nodes in the wavefunction can change precipitously, with a corresponding change of more than an order of magnitude in the decay constant.

One might ask whether the α-particle wavefunction, when the α-particle is first formed in the nucleus, might be better represented by a Gaussian wavefunction with no nodes rather than an eigenstate of the approximate potential of the α-particle due to the rest of the nucleus? This could cause the α-particle wavefunction to change progressively in a manner somewhat different than that advocated here, perhaps even causing departures from exponential decay. However, such a treatment would ignore the very large transition rates between a Gaussian wavefunction and the eigenstates. For instance, *Shankar* [1994] in chapter 18 of his **Quantum Mechanics** book has discussed the inadequacy of a treatment of spontaneous decay which ignores the quantum nature of the electromagnetic field.

The depth of the nuclear potential well is determined directly by the strength of the strong nuclear force, hence by the "strong coupling constant." A coupling constant is a number inserted in a theory to fix the strength of a force. We determine it experimentally, but theories exist which indicate that it may not be a constant over the history of the universe. Hence, we will discuss the relevant parts of these theories in other sections of this chapter.

3. Isotopic Distributions of U

Uranium isotopes ^{238}U, ^{235}U, and ^{234}U occur in the percent abundances of 99.27%, 0.72%, and 0.0055%, with other isotopes only occurring in trace amounts. The half-lives of these isotopes are 4.47×10^9 years for ^{238}U, 7.04×10^8 years for ^{235}U, and 2.47×10^5 years for ^{234}U. A condition known as *radioactive equilibrium* occurs when the activities of successive members of a decay chain are equal. The activity is defined as the decay constant (which is the natural logarithm of two divided by the half-life) times the number of atoms in the sample.

Figure 6 shows an analogy between fluid flow and the decay of the atoms in the ^{238}U to ^{234}U series. The level of the fluid in a bucket is a result of a balance between the rate of inflow and the rate of outflow. For a given level of fluid in the bucket, a proportional amount of pressure is produced at the bottom of the bucket, where the valves are

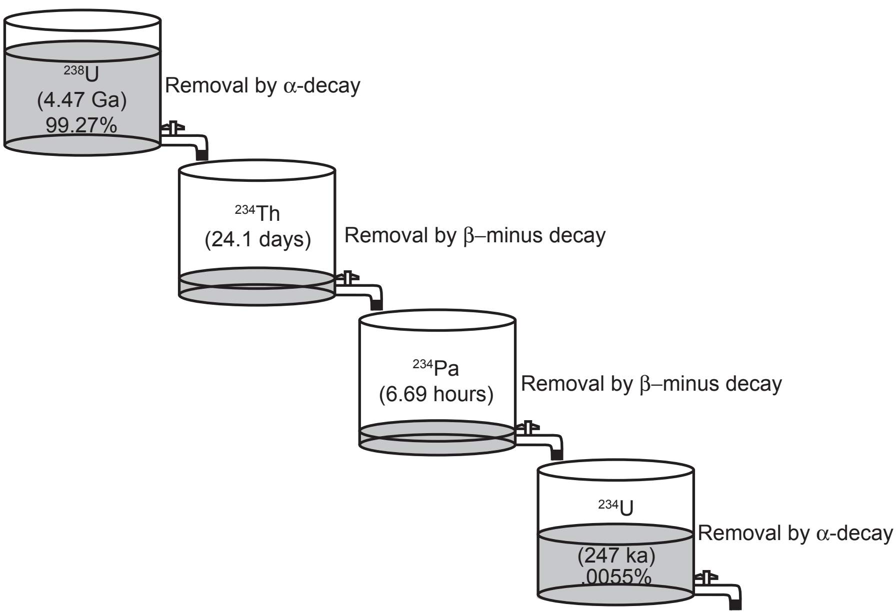


Figure 6. Equilibrium levels of fluid flowing out of buckets through valves that are not opened to the same setting. This forms an analogy to radioactive equilibrium of the ^{238}U decay series.

located. This is analogous to the amounts of radioactive parent atom present. However, the rate of decay also depends on how wide open the valve is, which is analogous to the half-life. The most probable decay mode of ^{238}U is α-decay, which produces ^{234}Th. Thorium-234 undergoes β minus decay with a half-life of 24.1 days, producing ^{234}Pa. Protactinium-234 then also undergoes β minus decay with a half-life of 6.69 hours producing ^{234}U. Thus ^{234}U is in the decay chain of ^{238}U, and radioactive equilibrium does exist because 0.0055 times the decay constant of ^{234}U is the same as 99.27 times the decay constant of ^{238}U. Departures from radioactive equilibrium exist in some samples [*Thurber*, 1962; *Chalov et al.*, 1966; *Chalov and Merkulova*, 1966, 1968] but the departures are relatively small.

The variations may possibly be explained in terms of the difference in relative solubility of ^{234}U and ^{238}U starting from hexavalent and tetravalent U in compounds and their decomposition products [*Chalov and Merkulova*, 1966; 1968]. Thus, a fraction of the ^{234}U atoms present in a mineral lattice will have formed by radioactive decay starting from ^{238}U. Due to the recoil of a nucleus during α-decay, a significant number of daughter nuclei will lose their former link with the mineral lattice. These daughter ^{234}U nuclei will as a result be, on the average, found in different linkages as compared to the ^{238}U nuclei. This was Chalov and Merkulova's explanation for why they found different rates of dissolution of ^{234}U and ^{238}U in their laboratory experiments. Working together with Tuzova, Chalov and Merkulova attempted to use this difference in solubility to obtain an age of the Aral Sea (southern Kazakhstan and northern Uzbekistan) [*Chalov et al.*, 1996]. Their result was 150±30 ka. However, some fragile assumptions were needed to arrive at this number, and such ages are not well accepted even among evolutionists.

From a young-earth viewpoint, it is easy to point to these fragile assumptions to invalidate age determinations such as those just mentioned. However, with an earth of only some thousands of years old, it is difficult to explain the bulk of the approximately equal ratios without an episode of accelerated decay. Starting from an arbitrary initial state, it takes more than one half-life of ^{234}U to establish equilibrium, implying an age of the samples very much larger than straightforward Biblical interpretation would indicate.

Figure 7 shows the graph of the ^{234}U abundance versus time, assuming the ^{234}U starts with a 100% abundance, or was equal in abundance to that of ^{238}U. One sees that, for this starting assumption, and assuming no accelerated decay, an age of the earth of at least four million years is implied. A possible alternative assumption is to assume that there was no ^{234}U at all at the start.

Figure 8 shows the result of that calculation. Assuming no accelerated decay, this assumption thus implies an earth age of at least 1.2 million years.

To justify the young-earth viewpoint, one would be logically correct in claiming that the rocks may have been created already in a state of radioactive equilibrium, with no time needed to reach that state. However, a more natural explanation seems to be provided by accelerated radioactive decay. We do not know the original ratio of ^{234}U to ^{238}U in the created materials of the early earth, but if we make some reasonable guesses, then a period of accelerated decay would adjust this ratio to the 0.0055% ratio presently found in the bulk of earth

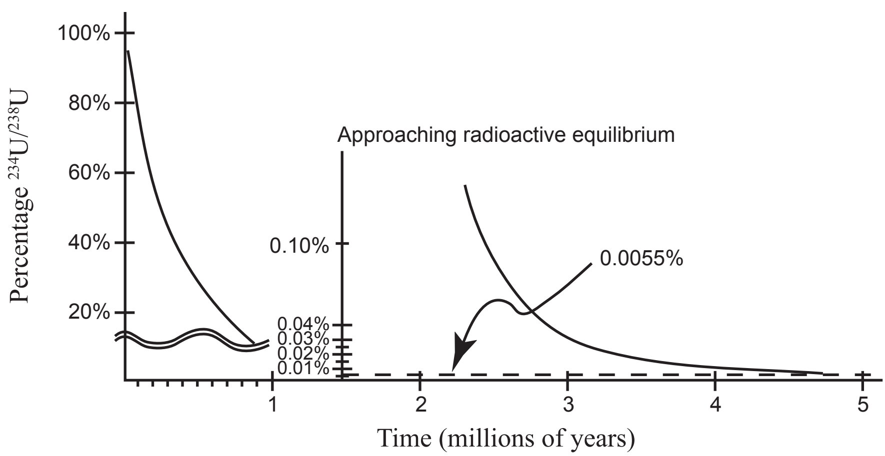


Figure 7. The percentage $^{234}U/^{238}U$ as a function of time, assuming that $^{234}U/^{238}U$ begins at 100%. The timescale shown assumes that no accelerated decay occurred.

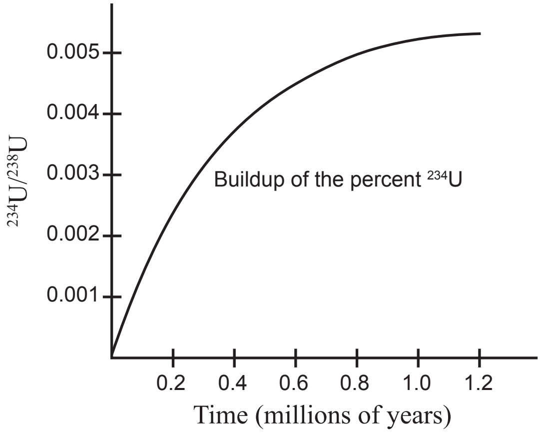


Figure 8. The percentage $^{234}U/^{238}U$ as a function of time, assuming that it begins at 0%.

materials. This may be evidence that such accelerated decay did, in fact, occur. Furthermore, by the time of the end of the acceleration episode, radioactive equilibrium would have been in existence, and decay rates of U much smaller, possibly even zero. It could even be that the decays of ^{234}U and ^{238}U were accelerated by different amounts, as long as the ratios of their decay rates approached the present-day values late in the episode. This would ensure that the 0.0055% value was reached. The intermediate stages in the path from ^{238}U to ^{234}U involve the relatively short half-lives of the β-decays of ^{234}Th and ^{234}Pa. Thus, acceleration of these intermediate stages produces a negligible effect, since they are already almost instantaneous on the timescales of interest.

The ^{235}U abundance, compared to ^{238}U, also seems to support this point of view. If the initial abundances of these two isotopes were of the same order of magnitude, then several half lives of ^{235}U are needed to establish the present 0.72% and 99.27% isotopic abundances, implying sample ages of a few billion years [*Chaffin*, 1985]. As in the ^{234}U cases, we do find slight variations in ^{235}U percent abundances between different minerals collected at different sites (see for example [*Malyshev et al.*, 1977]). However, the variations are small. To advocate a young earth without accelerated decay or very rapid initial decay after the creation of the elements, one seems forced to assume that the U isotopes were created in isotopic percent abundances approximating those found today [*Chaffin*, 1985].

4. The Oklo Data—A Constraint on Accelerated Decay?

In 1976, a Russian physicist published a letter to *Nature* which pointed out the relevance of the Oklo data to constraining possible variations of the nuclear force over the history of the earth [*Shlyakhter*, 1976]. More detailed discussions of the problem have since been published by other authors [*Damour and Dyson*, 1996; *Fujii et al.*, 2000]. Along with Molgaard, I have also done some recent work on the subject [*Chaffin and Molgaard*, 2003]. Oklo is a location in Gabon, Africa where some French scientists discovered more than a dozen reaction zones. In these zones fission product elements and depleted U led to the inescapable conclusion that former nuclear reactors existed in this Precambrian geological formation. The formations have been fitted into a Precambrian interpretation according to uniformitarian ideas about the geological setting, and would correspond to an age of about 2 billion years on the uniformitarian timescale. The abundances of ^{149}Sm, ^{238}U, and other isotopes have been measured in core samples. A development by *Fujii et al.* [2000] leads to the equation:

$$\frac{N_{147}(t_1)+N_{148}(t_1)}{N_{149}(t_1)} = \frac{\dfrac{\sigma_{f235}kY_{147}}{\sigma_a}\left[1-exp\left(\sigma_a\phi t_1\right)\right]+\left(R_{147}^{nat}+R_{148}^{nat}\right)}{\dfrac{k\sigma_{f235}Y_{149}}{\sigma_a-\sigma_{149}}\left[exp\left(-\sigma_{149}\phi t_1\right)-exp\left(-\sigma_a\phi t_1\right)\right]+R_{149}^{nat}\,exp\left(-\sigma_{149}\phi t_1\right)} \tag{1}$$

In the equation, $N(t)$ represents the measured isotopic abundances of the various Sm isotopes indicated by the subscripts, the σ values are the present-day cross-sections of the isotopes for absorption (a) or fission (f), the Y values are the fractional fission yields, the R values are the relative fractional natural abundances of the Sm isotopes, and t is the time. For more details, see the paper by *Fujii et al.* [2000]. It happens that the cross-section for absorption of neutrons by ^{149}Sm has a very large resonance peak at $E_r = 0.0958325$ eV. If this peak's position had shifted by more than about 0.01 eV, the calculated Sm cross-section would no longer match the data [*Chaffin and Molgaard*, 2003]. It cannot be ruled out, however, that two or more factors may have changed concurrently, causing one factor to cancel out the effect of the other. In any case, the Oklo data may indicate that coupling strengths could not have been too much different from today's values at the time of the reactions.

Table 1, column 2, shows the values of the effective cross-section σ_{149} which satisfies the above equation (1). These values were found by *Chaffin and Molgaard* [2003] by an iterative procedure using *Mathematica*. Column 3 shows the results of *Fujii et al.* [2000] for comparison. The results were obtained using data for Oklo reactor zone 10. One sees that the various samples give an average value of 90.3±7.4 kilobarns (1 barn = 10^{-24} cm^2). Here the 7.4 kilobarns is the standard deviation of the four sample results.

Table 1. Results of calculations for Oklo samples.

Sample	σ_{149} **(kb)**	**Fujii *et al.* Results**
SF84-1492	98.1	99.0
SF84-1485	83.0	83.8
SF84-1480	95.0	96.5
SF84-1469	85.0	85.6
Standard Deviation	7.4	7.6
Average	90.3	91.2

In a simple nuclear model in which a square well is used for the potential seen by the neutron inside the nucleus, the ^{149}Sm cross-section is related to the depth V_0 of the potential well. As *Weber et al.* [1982] showed, the resonant energy E_r is a constant minus V_0. Hence, a change in the nuclear force coupling constant is equivalent to a change in V_0, which is equivalent to a change in E_r. An adequate model for the ^{149}Sm neutron absorption cross-section as a function of energy is given by the Breit-Wigner shape:

$$\sigma_r = A\frac{\Gamma_n \Gamma_r}{\left(E - E_r\right)^2 + \Gamma_{tot}^2/4} \tag{2}$$

In this expression the widths Γ do not depend directly on the depth V_0 of the potential well, so the spread in values of 7.4 kilobarns can be related to a spread in values of V_0. For ^{149}Sm, E_r is 0.095835 eV, hence calculations show that a change of 7.4 kilobarns in σ_r corresponds to a change in E_r of ±0.0102 eV.

Assuming that the change in the nuclear force is due to a change in the strong coupling constant, a change in E_r of ±0.0102 eV for ^{149}Sm would correspond to a change of the same order of magnitude in the V_0 for the ^{238}U. For ^{238}U, the half-life for α-decay is 4.47×10^9 years and the V_0 is 110.5 MeV.

As discussed earlier, and represented in Figure 3, slight changes in the depth of the nuclear potential can cause a precipitous change in the α-decay half-life. The precipitous change is due to the change in the number of nodes in the α-particle wavefunction. This can cause a change in the decay constant λ by a factor of 13.5, or more than one order of magnitude. Hence, the Oklo data do provide a constraint on the difference in the half-life at the time of the Oklo reactions and the present. Half-life differences of more than one order of magnitude would seem to be ruled out, unless two or more factors may have changed concurrently, with each effect canceling the other. Since the Oklo rocks are interpreted as Precambrian this brings up the question of when the reactions may have occurred. They could have occurred long after the deposition had occurred, but since the deposits are sedimentary it seems unlikely that they could have been from early in Creation week.

In *Chaffin* [2000b] it was pointed out that radiohalos provide a constraint on possible variations in the energies of α-particles emitted in radioactive decay. *Gentry* [1986] has pointed out the constancy of the halo radii gathered from various geologic strata. Since the radii of halo rings are slightly dependent on the dose of radiation and the size of halo inclusions, an exact constraint on the α-particle energy cannot be maintained. Using the variable well depth models proposed here (discussed in Section 2), it is possible to show that, relaxing the requirement of exactly the same halo radii, a change in α-particle emission energy of 10% or so corresponds to a change in decay constant by a factor of about 10^5. Using a more realistic diffuse boundary potential, variations in the decay constant or 10^5 to 10^8 can occur in some cases. Contrary to what the combination of halo data with these simulations show, the Oklo data seem to be more restrictive and to dictate a change of decay constant by not more than about one order of magnitude. However, that would only correspond to the time in earth history when the Oklo chain reactions were occurring, or at least to the last stages in those reactions when the Sm absorption occurred. At other times the possibility of larger decay rate changes (more accelerated decay) remains open.

In the next few sections we will explore the theory of how the changes in coupling constants might have occurred.

5. Topology and Strings

Multidimensional string theories lead to a branch of mathematics known as *topology*. This, of necessity, is what happens when one considers these extra coordinates, or dimensions. An *n-dimensional manifold* is a space which can be transformed into a connected polyhedron, and such that every point can be surrounded by a collection of other points which is equivalent to the interior of an n-dimensional ball [*Alexandroff*, 1961; *Nash and Sen*, 1983; *Pontryagin*, 1999]. For example, the surface of a sphere is a two-dimensional manifold, which mathematicians write as S^2 (pronounced *S-two*, not *S-squared*). One needs two numbers to specify a point on this manifold, hence the number 2 means it is two-dimensional. Another two-dimensional manifold is the surface of a torus, T^2. For precise, mathematical purposes, the sphere S^2 and the torus T^2 are distinct entities, and should not be confused.

For example, suppose we are trying to describe the motion of a pendulum (Figure 9). Initially, let us suppose that the pendulum is swinging back and forth, staying perfectly within the confines of a vertical plane. Then we could draw a line, or projection, down to the point on a flat, horizontal surface directly below the pendulum ball. A single

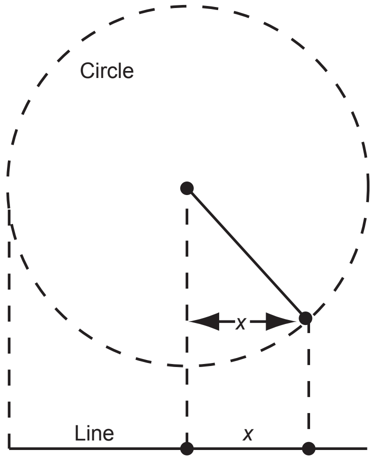


Figure 9. The position of a pendulum bob, confined to move in a single vertical plane, can be completely specified by a single linear coordinate *x*, provided the pendulum does not swing over the support's level. If the pendulum is free to swing higher than the support, then the circular topology is needed to specify the position. (Figure drawn after *Rourke and Stewart* [1986].)

coordinate *x* would then suffice to specify the position of the pendulum ball, this coordinate specifying the position on a *straight line*. However, for large oscillations of the pendulum, and if the pendulum was fixed by a universal joint at the top, the pendulum could swing over the top. Our single coordinate would then not suffice to distinguish positions above the support from positions below the support. Hence, a more correct mathematical model for the pendulum would be the *circle*. If, in addition, the pendulum were now able to swing in all directions, and not confined to one vertical plane, then the circular topology becomes inadequate, and a more correct model would be the *sphere*, S^2.

Suppose now that the problem is that of two pendulums, each confined to move in a vertical plane but allowed to swing over the top. The two pendulums move *independently* of each other, assuming positions on two different circles. The combined coordinates now have a different topology, the topology of the torus, T^2.

One of the early pioneers of topology was Henri Poincaré, whose active work on the subject occurred during the 1890s up to his death in 1912. Poincaré analyzed different surfaces by thinking in terms of deformations of loops, which links to what are now called *homology* and *homotopy*. In mathematical topology, homology theory concerns itself with the question of the number of *holes* in the space. Shown in Figure 10 are three curves, *a*, *b*, and *c* on the surface of a torus. The curves *a*, *b*, and *c* have something in common; they cannot be shrunk to a point by continuous sequence of deformations. For curves *a* and *b* it is because the hole is there. For curve *c* it is because the curve is wound around a closed circumference and cannot be shrunk unless one cuts the curve, moves it, and then pastes the ends together. In topology, this is described by stating that *a* and *b* belong to the same homology class, whereas *c* belongs to a different class. Similarly, the concept of homotopy concerns itself with deforming loops. Two loops are homotopic if they can be continuously deformed into each other. These concepts, and others, become important tools in analyzing topology and ultimately multidimensional string theory.

Within the last five to ten years, research has uncovered numerous *dualities* relating different limits and formulations of string and membrane theories. *Duff* [1998] and *Greene* [2000] have discussed the duality between ordinary vibrational modes and winding modes of a string (see Figure 11).

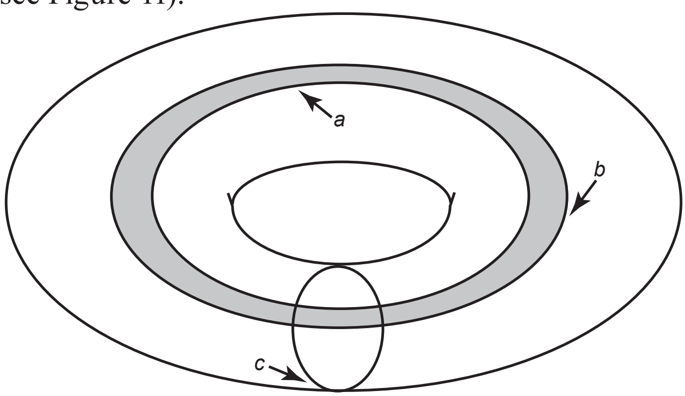
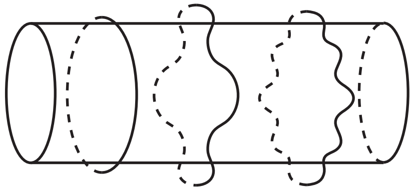
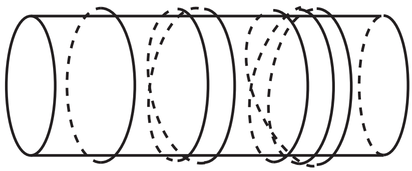


Figure 10. Three closed curves on the surface of a doughnut (torus) illustrate inequivalent and equivalent closed paths. Curves *a* and *b*, which bound the hatched area, can be smoothly distorted into each other, whereas curve *c* winds around a different direction and cannot be distorted into *a* or *b*, without cutting and pasting the ends. (Figure drawn after *Eguchi et al.* [1980].)



Ordinary vibration modes



Winding modes

Figure 11. The ordinary vibration modes of closed strings (top) and the winding modes (bottom). In the equations of string theory, these two modes carry energy, and exchange roles when the radius of the compactified dimension moves from small to large.

A value of the radius for compactified dimensions leads to the same results or equivalent results for a different radius, in which the winding modes and ordinary vibrational modes change roles in the equations of the theory [*Dai et al.*, 1989]. Another type of duality relates the *strong coupling* limit of one theory to the *weak coupling* limit of another. A *coupling constant* is a number giving the strength with which an elementary particle is coupled to the field that it experiences. For example, the coupling constant for interaction with the electromagnetic field is the electric charge. In some work by *Lykken* [1996] and *Witten* [1996], these authors speculated that, contrary to previous thought (see *Kaplunovsky* [1988, 1992]), strong coupling limits of certain string theories were more relevant to accelerator physics. This led to some more realistic applications of string theory than had previously been possible (see *Nath and Yamaguchi*, [1999]).

6. Compact Circumferences and Coupling Constants

Weinberg [1983a] used generalized Kaluza-Klein models having

4+N dimensions to find a relation between coupling constants and the root-mean-square (rms) circumferences of the compactified dimensions. As discussed by *Chaffin* [2000a], the original Kaluza-Klein model had only one extra dimension besides the usual four of ordinary spacetime. *Witten* [1981] discussed the generalization to the case where there are more compact dimensions. Weinberg applied this idea to reduce some assumed higher-dimensional equations of gravitation theory to the four-dimensional case, and worked out the results of his equations for some simple examples. These examples assign an assumed topology to the compactified dimensions, and then calculate the rms circumferences. For one example, he assumed that the topology corresponded to the symmetry group **SO**(N+1), the group of rotations, contiguous to the "leave-it-alone" or identity rotation, in N+1 dimensional space. (A *group* is a set of elements plus a rule of combination of pairs of elements, satisfying certain requirements, including that every element has an inverse.) This gave the result for the SO(N+1) coupling constant:

$$g = \left(\frac{\kappa}{R}\right)\left[\frac{1}{2}\left(\mathrm{N}+1\right)\right]^{1/2} \tag{3}$$

Here, $\kappa^2 = 16\pi G$, where G is Newton's gravitational constant, R is the radius of this (N+1)-dimensional shape with topology analogous to that of a sphere. Thus, for a highly symmetrical topology such as this, all the coupling constants would be the same. In the real world, we know that the strong, electroweak, and gravitational constants are different, but here we are dealing with a simplified example to illustrate possible "real" behaviors.

Weinberg [1983a] also considered an example having the symmetry SU(3), the group of all unitary 3×3 matrices with determinant of plus one. In this example there are two different possible values for coupling constants g and g',

$$g = \frac{\sqrt{2\kappa}}{R} \tag{4a}$$

and

$$g' = \sqrt{\frac{2}{3}}\,\frac{\kappa}{R} \tag{4b}$$

Thus, the ratio of the two coupling constants is the square root of 3, and does not depend on the radius R of the extra dimensional shape.

Candelas and Weinberg [1984] generalized these results to include the effects of quantum fluctuations of matter fields on the vacuum, and found slightly modified versions of the earlier relations between the radii R of the compactified dimensions and the coupling constants. They also generalized some considerations of *Rubin and Roth* [1983] which attempted to relate the radii of the compactified dimensions to the average temperature of the matter fields contained in the universe. The change of the compactified radii with temperature can be understood physically through the Casimir effect [*Hawking*, 1996; *Chaffin*, 2000a]. In modern quantum field theory there is a zero-point energy, which can be thought of as a sea of virtual particles arising from the vacuum, and which cannot be eliminated. The Casimir effect is a force between two parallel conducting plates caused by differences in zero-point energy of the electromagnetic field. In a similar manner, at zero temperature, the gravitational zero-point energy of the Kaluza-Klein ground state leads to the collapse of the fifth dimension, but in that case we deal with the topology of the compactified dimensions, not with parallel plates. In the parallel-plate case, if a gas of photons at fixed temperature is introduced between the plates, the net pressure on the plates will be the sum of two contributions: the positive pressure from thermal photons, of constant magnitude, and the negative Casimir pressure, varying in inverse proportion to the fourth power of the plate separation. The negative Casimir pressure arises because the short distance between the plates prevents standing waves of certain wavelengths from existing between the plates. In particular, it excludes long wavelengths. If the plates start out close together, the negative Casimir pressure is stronger than that of the thermal photons and the plates collapse. If they start out at a distance such that the Casimir pressure is weaker, then the plates will fly apart with nothing to stop the separation. The thermal photon pressure changes as the plate separation changes, but only as (separation)$^{-4/3}$; that is, much more slowly than the Casimir pressure.

Candelas and Weinberg [1984], and before them *Rubin and Roth* [1983], attempted to extrapolate from the parallel-plate case to a realistic Kaluza-Klein model. Such a model would remove the artificial constraints of an assumed external geometry and an assumed time-independent internal geometry. Realistic models would also involve more than just one compact dimension, with compactification brought about by vacuum expectation values (VEVs) for non-gravitational fields, and would include fermionic (half-integral spin) fields. The presence of curvature in both the compact and non-compact dimensions, the response of the VEVs to changes in temperature, and fermion degeneracy pressure might well all contribute to behavior very different from that observed in the parallel-plate case.

This idea provides a possible mechanism for changing the radii of the compact dimensions as the universe expands and its background temperature changes. Early in Creation week, it may be that the mechanism could also work in a young-earth model.

7. Manifolds and Coupling Constants in Superstring Theory

In superstring theory, we need to link a 10-dimensional "manifold," which is simply a framework which can be smoothly described by ten independent coordinates, with our observed four-dimensional spacetime. If the extra six dimensions are curled up into a compact space, this simply means that every point of four-dimensional spacetime has one of these compact six-dimensional spaces associated with it. (In more recent theory, eleven-dimensional membranes are wrapped up to make ten-dimensional superstrings, but that is just an unneeded complication as far as we will be concerned.) If the size of the compactified six-dimensional space is small compared to the scale of everyday life, we would not directly detect the effect of these extra dimensions [*Chaffin*, 2000a; *Hawking*, 2001].

At high enough energies, higher even than those of the abortive superconducting supercollider, the SSC (which began but did not complete construction in Texas), a particle accelerator would be likely to detect the presence of the so-called Kaluza-Klein excitations or Kaluza-Klein modes. In quantum mechanics, waves are associated with all particles. When we consider string theory, we find that if a spatial dimension is curled up, then the momentum p associated with the waves wrapping around this dimension will be quantized, with values $p = nh/(2\pi R)$, $n = 0, 1, 2, 3, \ldots$, and h is Planck's constant, while R is the radius of the compactified dimension. In this picture the masses of the quantized excitations, the masses m_n of the particles, are given by $m_n^2 = m_0^2 + n^2h^2/(4\pi^2R^2c^2)$, where m_0 is the mass of the mode with zero momentum and c is the speed of light.

Particles can be divided into fermions (half-integral spin) and bosons (integral spin). It is possible that the fermions, or some of the fermions, may not have Kaluza-Klein excitations [*Dienes et al.*, 1999]. This is dependent on exactly how the extra dimensions are compactified. If the fermion corresponds to excitations located at the fixed points of an *orbifold*, then no Kaluza-Klein excitations exist. In mathematically precise formulations of topology, an *orbifold* is a way of smoothing over or "blowing up" certain fixed points at which different coordinates must be joined [*Dixon et al.*,1985].

The term *orbifold* originated in a graduate mathematics class taught by William P. Thurston in 1976–1977 [*Thurston*, 1997, 2002]. For an n-dimensional space R^n, an *orbifold* is a structure constructed by using a finite group G, and considering equivalence classes of points in R^n modulo group G. The equivalence classes are then considered as the points of the orbifold. The technical definition is given by *Thurston* [1997, 2002], but we will not go into the details here. A simple, rough example is formed by considering the finite group Z_2 and its action on R^3. The group Z_2 has two elements, the identity element and the operation of reflection through the *y*-*z* plane. A point (x, y, z) is reflected to the point $(-x, y, z)$. One could imagine a mirror in the *y*-*z* plane (Figure 12). The two points (x, y, z) and $(-x, y, z)$ are considered part of an equivalence class, and the space of the orbifold is thus the half-space $x \geq 0$ (see Figure 12). Orbifolds were introduced into string theories in the mid 1980s. It is difficult to trace who first introduced them, but they were used in a Ph. D. thesis by *Dixon* [1986].

In the actual multidimensional string theories, we need to make contact with the "real" world of four spacetime dimensions. The ten-dimensional superstring theory must compactify six of the

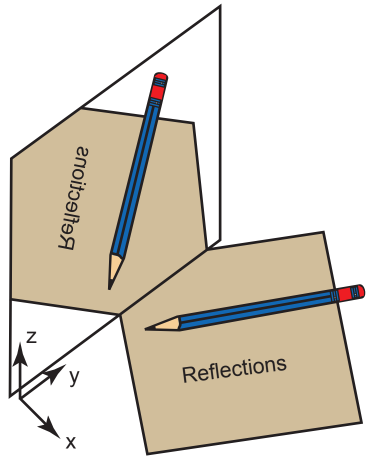


Figure 12. Considering each point (x, y, z) as equivalent to its reflection ($-x$, y, z) leads to the quotient space.

dimensions on a six-dimensional compact manifold. Particle physicists have, in the last fifteen years, spent a great deal of time studying just how to do this. Fortunately, mathematicians have been studying topology since the time of Poincaré in the late 1800s. While they have not fully developed all the machinery needed by the string theorists, two mathematicians, Eugenio Calabi and Shing-Tung Yau had studied a type of six-dimensional space, known as a Calabi-Yau space (pronounced *cah-lah'-bee-yah'-oo*) which particle theories needed [*Greene*, 2000]. The topology of this space, with the requisite number of "holes," seems to be right to allow the known quarks and leptons to be described in terms of string theory. The quarks and leptons are grouped into three "families," which are allowed by these Calabi-Yau shapes. They allow description in terms of representations of the $\mathbf{SU}(3)\times\mathbf{SU}(2)\times\mathbf{U}(1)$ group of the so-called *standard model.*

The Calabi-Yau spaces have "holes," and in superstring theory the sizes of coupling constants are related to the diameters of these holes [*Greene*, 2000]. Figure 13 shows a cross-section through a Calabi-Yau space. In some cases, Calabi-Yau manifolds have been constructed for which it has been possible to find the coupling constants from first principles [*Arnowitt and Nath*, 1989; *Nath and Arnowitt*, 1989a, b].

Through their effects on the possible vibrations of strings, Calabi-Yau shapes influence the detailed properties of the existing particles. *Strominger and Witten* [1985] showed that the way that the various multidimensional holes intersect and overlap with each other actually determines Yukawa couplings and hence the masses of the matter particles. *Yukawa couplings* are numbers in field theory equations which determine the strengths of fermion interactions with scalar fields such as the Higgs fields or string theory fields called the dilaton or moduli fields. Their specification is needed for a complete theory, over and above the specification of the gauge coupling constants of the symmetry groups **SU**(3), **SU**(2), and **U**(1) of the standard model [*Bailin and Love*, 1986, p. 248]. According to the Higgs boson theory of the standard model, the Yukawa coupling constant multiplied by the vacuum expectation value of the Higgs field gives the mass of a particle of matter. Thus we find that string theory provides us with a framework for answering some very important questions.

The new theory of recent years is called M-theory, where M may stand

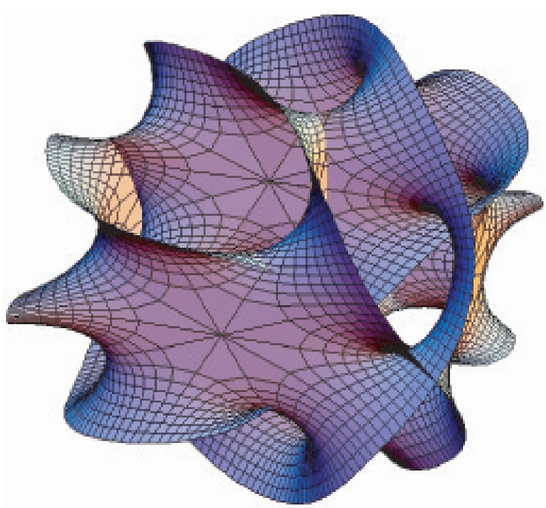


Figure 13. A cross-section through a six-dimensional Calabi-Yau shape, generated with *Mathematica*.

for membranes, matrices, and other things. Protagonists seem to prefer to leave the meaning of the "M" open. This theory involves membranes rather than strings of zero diameter. This means that six-dimensional Calabi-Yau shapes are replaced by seven-dimensional manifolds known as Joyce manifolds, after *Joyce* [1996a, b, c] who is credited with finding the techniques for their mathematical description.

Up to the present, a glaring failure of string theory has been found in superstring theory. It has been impossible, starting from first principles, to calculate which Joyce manifold, or in the limit where membranes shrink to strings, which Calabi-Yau manifold is a solution to the basic Lagrangian equations. Stated in other language, the theorist cannot determine which vacuum is the true vacuum. Instead the approach used is *phenomenological*. One searches for manifolds that seem to provide correct particle properties, but these manifolds are found from guesses rather than by solving the equations.

Also, it is sometimes stated that there is only one parameter in superstring theory. *Dabholkar and Harvey* [1989] wrote: "In string theory, the only really fundamental constant is the string tension μ." *Witten* [1984] wrote:

> An observation that is not essentially new, but still worth mentioning, is that—as befits a possible unification of all interactions—the superstring theory has no adjustable parameter.

Witten called attention to what is called the dilaton field in superstring theory [*Damour*, 2003]. Witten went on to speculate that, when someday it became possible to calculate the vacuum states from first principles, the minimum of a non-trivial potential for the massless scalar dilaton field would represent the true vacuum and leave no free parameters at all. However, these authors assume that there is only one unique vacuum solution of the string theory equations, and that it is immutable, unchangeable over the history of the universe. While it appears that this issue is yet to be decided [*Duff et al.*, 2002], it seems likely that there could also be solutions in which the strong force coupling constant changes relative to other coupling constants. In particular, the size of the extra dimensions is tied to the dilaton field [*Veneziano*, 2004], but the assumption is sometimes made that all of the compactified dimensions must be the same size. This need not be the case.

Other string theorists may be quoted to show this alternative viewpoint. *Page* [1987] wrote:

> The superstring theory itself might predict only certain combinations of the physical constants, leaving several independent combinations that could be predicted only by the WAP *[Weak Anthropic Principle]* (and then probably only within a certain range allowed by the existence of observers).

In his discussion, Page thus advocates what many evolutionary proponents advocate, the WAP which is that we observe the constants and other values that we do because if these constants did not have these values then no intelligent life could have evolved or could exist and there would be no observers. To a Biblical creationist, this evolutionary paradigm is replaced by the realization that God has designed our world so that we will exist in accordance with His design. Creationists who take the Bible's statements about history as being factual do believe in a young earth and that man was created by a direct act of God. But this is leading us away from Page's other point, which is that the string theory may allow solutions which are richer in variation than Witten, Dabholkar, Harvey, etc. seem to advocate.

8. Unified Theories: Food for Thought?

In 1974 the **SU**(5) theory of combined strong, weak, and electromagnetic interactions was proposed (see *Georgi and Glashow*, [1974] and *Georgi et al.,* [1974]). The **SU**(5) theory receives its name because it is modeled after five by five special unitary matrices (hence the nickname **SU** standing for special unitary), *special* meaning they have determinant of plus one. This theory allowed all the families of quarks and leptons to be combined into representations of the **SU**(5) group, which means that we only needed particles called gluons, W^+, W^-, Z^0 bosons, and the photon to describe the forces between the quarks and leptons. (*Georgi* [1989] has given a popular-level description of how this theory was formulated.) Basically, the **SU**(5) theory had only one "coupling constant." In accord with previous discussion, the "coupling constant" may be thought of as a number which describes how much force originates from placing particles of known type a certain distance apart. Each type of force has its own coupling constant, but the **SU**(5) theory implied that the coupling constants for strong, weak and electromagnetic forces all originated from a single constant, diverging into their various values as the energy of the interactions is lowered from high energies down to low energies. The reason for the divergence of these values has to do with what is called *renormalization*, and with the *effective field theory* which results from performing the renormalization appropriate to a given energy scale. In quantum field theory, a particle is surrounded by a cloud of virtual particles, which cloud will be penetrated to varying degrees by a second particle interacting with it [*Georgi*, 1989]. A more energetic particle penetrates further. For example, a real particle with positive electric charge will be surrounded by pairs of virtual electrons and positrons. On the average, the virtual positrons are pushed farther away from the real particle, while the virtual electrons are nearer to it. So on the average, the real particle has more negative charge near to it than far from it. A second real particle, depending on its energy, will penetrate this cloud to a lesser or greater degree. For this reason, the effective interaction depends on the particle energy, and the coupling constant of electromagnetic interactions is less for smaller energies. In the case of the strong force, the gluons cause the force to get weaker at larger energies [*Georgi*, 1989, p. 432; *Dimopoulos et al.*, 1991; *Franklin*, 2005, p. 452]. The fine structure constant, which is approximately 1/137 at low energies, has been experimentally measured as about 1/128 at an energy of 58 GeV [*Levine et al.*, 1997]. Similarly, the strong coupling constant α_s has been measured as about 0.119 at 91 GeV (the mass-energy of the Z-boson), whereas it decreases to about 0.110 at 206 GeV [*Bethke*, 2002].

Renormalization theory says that not only the coupling constants, but also the masses of particles appear to vary on different energy scales [*'t Hooft*, 1980; *Nelson*, 1985]. While quantum theory connects this effect to varying energy scales, the basic ideas are actually much older. J. J. Thomson discovered the so-called electromagnetic mass in 1881 [*Thomson*, 1881]. Thomson correctly noted that a charge moving through a dielectric experiences a resistance, which is non-dissipative, and hence is best described by an additional contribution to the mass. The resistance is comparable to that of a sphere moving through a perfect fluid. Motion of the sphere is impeded by the presence of the fluid. Using James Clerk Maxwell's theory of electricity and magnetism, Thomson showed that the charged sphere, moving through the dielectric, would experience an additional mass. Thomson's equation for the new mass m is:

$$m = m_0 + \frac{4}{15}\frac{\mu_0 e^2}{a} \tag{5}$$

where e is the charge, a is the radius of the sphere, and μ_0 is the magnetic permeability. While quantum theory does not assign a radius to the electron, the "vacuum polarization" effect is nevertheless a real effect [*Bjorken and Drell*, 1964, section 8.2; *Georgi*, 1989, p. 434]. In many laboratory experiments, the particles have low energy and are nowhere near the large energies that bring out these effects. However, for experiments involving modern particle accelerators, these effects become evident: the effective coupling constants and effective masses vary with energy.

The **SU**(5) theory of Georgi and colleagues had an unfortunate failure. It predicted the decay of the proton, with a half-life greater than 10^{29} years. As a result of this prediction, experiments were set up to detect this proton decay, and no conclusive evidence for such decays was found. The half-life of the proton, if not infinite, was shown to be higher than the range which the **SU**(5) theory seems to allow. Other unified theories based on other groups or on string theory are possible, and this is still an active field of research. For example, *Shiu and Tye* [1998] discussed the possible suppression of proton decay by an additional symmetry, while *Dienes et al.* [1998a, b] discussed a *higher-dimensional* mechanism involving selection rules for the Kaluza-Klein excitations which allow all proton-decay processes to have vanishing probability. In the **SU**(5) theory and in similar theories allowing proton decay, there are particles, either X-bosons or Higgs particles, which are responsible for the proton's decay. In the *Dienes et al.* theory, however, the proton does not have Kaluza-Klein excitations, which leads to a zero probability for its decay. (Technically, the proton is said to be restricted to the fixed points of an orbifold, at which point the probability for interacting with the X-bosons or Higgs particles is zero.) *Emmanuel-Costa and Wiesenfeldt* [2003], noting that the original considerations assumed the equality of two Yukawa coupling constants, have speculated that these couplings might be different, which could possibly save the **SU**(5) theory from extinction. Of course, these theories are untested at present, so the correct explanation for the lack of proton decay is still undecided.

Unfortunately, this also leaves open the question of whether or not the **SU**(5) theory was correct in predicting that there is only one gauge coupling constant at high energies. If the radii of compactified dimensions varied over the early history of Creation, then a related question also seems to be unanswered for us. Could the rates of α- and β-decay vary relative to each other over the history of the universe? This is an interesting question, and needs to be answered in order to correctly interpret radioisotope data. A start in this direction will be provided in the next section.

9. Kaluza-Klein Excitations, Technicolor, and the Fermi Coupling Constant

Gauge field theories by themselves provide no mechanism for giving the values of the coupling constants, because the coupling constants are just numbers which must be measured experimentally and inserted in the equations [*Weinberg*, 1983b]. We can measure how the coupling constants "run" with energy, as we have already discussed, but the basic starting values are not provided by the gauge field theory and no mechanism is provided for their time variation. Hence, in order to provide mechanisms for variations of coupling constants, one is forced to consider more ambitious theories, such as Kaluza-Klein theory or string theory. This means discussing theories which are at present somewhat speculative.

Nath and Yamaguchi [1999], considered the question of whether Kaluza-Klein excitations contribute to the so-called Fermi constant, which determines the fundamental rates of β-decays. Enrico Fermi, the

Italian-American of the Manhattan project, was responsible for the first realistic theories of β-decay, so this constant G_F, as applied in β-decay theory, is named after him. For the case of one extra dimension, Nath and Yamaguchi showed that to leading order in the ratio of the W boson mass M_W to the mass proportional to $1/R$ (the compactification scale mass M_R), the effective Fermi constant G_F^{eff} is given by

$$G_F^{eff} \cong G_F^{SM}\left(1+\frac{\pi^2}{3}\frac{M_W^2}{M_R^2}\right) \tag{6}$$

Here, G_F^{SM} is the value of the Fermi constant, which may be calculated from the standard model of quantum field theory. *Nath and Yamaguchi* [1999] comment that the standard model agrees very well with experiment without any assumptions about extra dimensions. For the case of more than one extra dimension, Nath and Yamaguchi derived a simple formula similar to the above but depending on the extra dimensions. From the results of standard model calculations, plus experimental measurements [*Abachi et al.*, 1996; *van Ritbergen and Stuart*, 1999], Nath and Yamaguchi showed that the energy M_Rc^2 was at least 1.6 TeV. This encourages particle physicists to hope that, with the completion of the Large Hadron Collider (LHC), expected in 2007 or so, evidence for these extra dimensions may be found (see *Kane* [1998] for a semi-fictitious account of expectations).

Now, because we are interested in the possibility of accelerated decay in the early universe, we need to take the discussion a step further than Nath and Yamaguchi did. In their paper, they only considered present-day measurements. Because of our interest in explaining radioisotope data in terms of a young earth, we may think as follows. If, over the early history of the universe, the radius of compact dimensions should change, then so would the mass scale M_R, and hence the value of the Fermi constant. Under the simplifying assumption that other factors in the equation do not change as radically as M_R does, decreases in the sizes of extra dimensions would increase M_R, and hence decrease the values of G_F. This in turn would mean that half-lives for β-decays of nuclei would become larger as the extra dimensions became smaller. Thus, one would expect accelerated decay to have occurred early in the history of the creation.

In particle physics today, there are rival theories including some called Technicolor models [*Chivukula et al.*, 2004]. In these models extra gauge bosons, with the same properties as the W and Z bosons except larger masses, should appear at the higher energies that should become available when and if the CERN accelerator upgrade is completed in about 2007. These models have extra coupling constants besides those of the standard model, and lead to equations for the Fermi constant very similar to the one given above, except that a scale parameter f plays the role of the M_R of equation (6) given above. Hence, time variation of the Fermi constant is possible in many different ways which will have to be sorted out when more data become available sometime after 2007.

10. Variation of Particle Masses: A Problem?

The depth of the nuclear potential well is determined directly by the strength of the strong nuclear force, hence by the "strong coupling constant." A coupling constant is a number inserted in a theory to fix the strength of a force. We determine it experimentally, but theories exist which indicate that it may not be a constant over the history of the universe. The principal coupling constants in modern physics are those of the strong, weak, electromagnetic, and gravitational interactions. Particles may be divided into sets according to the types of force to which they respond. The leptons include the neutrinos, the electron, muon, and tau particles. The neutrinos have no electric charge and hence do not experience the electromagnetic interaction. The electron, muon, and tau experience the weak and electromagnetic interactions but not the strong interaction. Hadrons are the types of particles which experience the strong interactions. The hadrons include the proton and neutron, as well as various heavier particles such as hyperons and mesons.

In considering possible variations in the strengths of the various forces, as indicated by changes in the coupling constants, it soon becomes evident that the masses of the particles could also possibly change. In fact, consistent modern theories seem to *demand* that such changes be a by-product of the changes in force strengths.

For instance, consider the mass of the proton and/or neutron (which are called nucleons). While significant unanswered questions still remain, theories of the nucleon mass have been formulated, based on the quark model plus some assumptions about the nature of the forces between quarks. These assumptions include that the force is basically due to the exchange of eight particles called gluons, plus contributions from exchange of pions and other bosons for larger distances. Xiangdong Ji, then a physicist at Massachusetts Institute of Technology, published in 1995 a separation of the nucleon mass into the contributions of the quark and gluon kinetic energies, the quark masses, and other contributions [*Ji*, 1995]. For instance, Ji's work shows that the contributions of the valence and sea quark masses amount to a contribution of 160 MeV out of the total of 939 MeV of mass-energy of the nucleon. Here the "valence quarks" are the two up quarks and one down quark that compose a proton or the two down quarks and one up quark that compose a neutron. The sea quarks are the virtual quarks that exist as virtual particles at any one instant of time. Ji's calculation ignored the small contribution of electromagnetic forces to the mass of a nucleon. According to *Calmet and Fritzsch* [2000], the nucleon mass "receives also a small contribution from electromagnetism of the order of 1%..." Both the neutron and proton have these electromagnetic contributions, even though the neutron is neutral, because the quarks inside the neutrons have non-zero charge, with a total of zero.

If one considers the mass of the electron, one soon notices that since the electron does not experience the strong force, then changes in the strong coupling constant would not affect the mass of the electron. This in turn would mean that as a result of a change in the nuclear force, the chemistry of everyday life could continue to operate nearly as it had before. The atom is largely empty space, with most of the mass concentrated in the small nucleus at its center. In the approximation that the nucleus does not move, energy levels of atoms and molecules are not affected by the nuclear force, only the energy levels of the nucleus. To calculate atomic energy levels, the fact that the nucleus does move is taken into account by replacing the mass of the electron by the so-called reduced mass, equal to:

$$\frac{m_e M_N}{m_e + M_N} \tag{7}$$

where m_e is the mass of the electron and M_N the mass of the nucleus. The present value of the proton-to-electron mass ratio μ is 1836.1526645. Hence, the reduced mass differs from the mass of the electron by a factor of 0.9994557. Past values can be inferred from studying molecular spectra such as those of H_2 molecules in distant gaseous clouds, which absorb the light coming to earth from distant quasar light sources. *Potekhin et al.* [1998] reported results indicating a larger value of the proton to electron mass ratio in light from the quasar PKS 0528-250. If $\mu = M_p/m_e$, the fractional change $\Delta\mu/\mu$ was found to be:

$$\frac{\Delta\mu}{\mu} = \left(8.3^{+6.6}_{-5.0}\right)\times 10^{-5} \tag{8}$$

Since the given limits of variation are one standard deviation errors, this result is also consistent with no change at all. More seriously, it illustrates that changes in the reduced mass have measurable consequences, if we assume that changes occurring on earth were also occurring elsewhere in the cosmos. Since light from distant stars originated in the past, then measurements should show such differences if they occurred throughout the universe.

A more recent analysis of light from the quasar Q 0347-382 yielded a similar result [*Ivanchik et al.*, 2003]:

$$\frac{\Delta\mu}{\mu} = \left(5.02 \pm 1.82\right)\times 10^{-5}$$

Here the error does not exceed three standard deviations, so the result hints at a variation but is also consistent with no variation.

However, a change of the mass of the proton by 0.08% would lead to transformation of protons into neutrons by electron capture. This would occur if the proton mass-energy increased from its present value of 938.28 MeV to a value greater than the neutron mass-energy of 939.57 MeV. The electromagnetic contribution to the nucleon mass can be calculated, as for example by *Genovese et al.* [1997]. The principal contributions are the Coulomb attractions and repulsions between the various quarks and the interactions of their magnetic moments. However, the neutron differs from the proton by the replacement of one down quark by an up quark. Hence, the difference in masses of the up and down quarks is another source of the neutron-proton mass difference. In this case, the masses of the quarks might not vary in the way that a naïve model might predict. Hence, variations in the strong coupling constant would not necessarily upset the fine balance between the masses of the neutron and proton.

Calmet and Fritzsch [2000] proposed a theory in which the masses of the light quarks, including the up and down quarks, would not vary at all, only the mass of the top quark. If this theory is correct, and the gluons have zero rest mass as commonly believed, then variation of the strong force could possibly occur without a noticeable change in either the quark or the nucleon masses. The changes would not likely be zero, due to various higher-order effects, but they could be small enough so that the reduced mass was not noticeably changed.

In standard electroweak theory, the Higgs boson is responsible for most of the mass of observed particles [*Taylor*, 1989]. The theory requires the Higgs particle to interact with all particles which have mass—the bigger the mass the stronger the interaction. The Higgs mass is at present unknown, since conclusive evidence for its existence does not yet exist [*Renton*, 2004]. In 2002, the electron-positron collider, LEP, at CERN in Geneva, Switzerland, was collecting data consistent with a possible Higgs particle with a mass-energy of 115 GeV. However, the accelerator had to be shut down to prepare for the construction of a new, more powerful accelerator, expected to be completed in 2007. As *Renton* [2004] discusses, indirect methods give an estimate of 92^{+130}_{-48} GeV for the Higgs mass-energy, a value which is consistent with the hint from CERN of 115 GeV. However, the confirmation of the Higgs particle awaits the construction of the new CERN accelerator.

In extended versions of electroweak theory, more than one Higgs boson exists. Such theories include the minimal supersymmetric standard model (MSSM) and grand unified theories (GUTs). In particular, some versions include, in addition to two Higgs particles with mass-energies of about 100–200 GeV, other Higgs particles with mass-energies between 10^{14} and 10^{16} GeV. Such particles have allegedly played a role in inflationary models of the universe [*Linde*, 1979, 1984, 1997], in which some driving force was needed to cause a rapid expansion of the universe. The fact that some Higgs particles are so much heavier than the others is called the *gauge hierarchy problem*, and although various solutions have been proposed [*Randall and Csaki*, 1996; *Witten*, 2002], the correct one is not known. Although CERN found some evidence for one Higgs particle near 115 GeV, the existence of these other Higgs particles is not known and is not likely to be known in the near future. If the heavier Higgs particles exist, it may be that their influence on the quark masses is also negligible, as in the Calmet and Fritzsch theory. On the other hand, they may not exist at all, and firm conclusions based on the properties of Higgs particles are not possible.

In *Calmet and Fritzsch* [2000] theory, the 100–200 GeV Higgs boson and its production of mass for quarks was considered. It was pointed out that the coupling of the light mass quarks and the electron to the Higgs field is an unknown which could even be zero. The theory becomes inconsistent unless the $W^{\pm}$ and Z^0 gauge bosons couple to the Higgs field, via the gauge coupling constants and the weak mixing parameter (which will be explained below in Section 12). However, the Yukawa coupling constant of the light quarks and the electron to the Higgs field could be very small, possibly even zero. *Quigg* [1997] assumed a Higgs vacuum expectation value of 176 GeV to get a value of about 3×10^{-6} for the electron Yukawa coupling and approximately 1.0 for the top quark Yukawa coupling. This interprets the very heavy top quark (mass-energy 178 GeV) as the only quark which couples strongly to the Higgs field. Other physicists [*Weinberg*, 1982] have also concluded that the Yukawa couplings of light quarks and leptons must be very small. This would explain why these quarks and leptons are much lighter than the W-particles.

In conclusion, it seems likely that the mass of the nucleon does vary with the strength of the nuclear force. However, the size of the variation may be small if theories similar to the Calmet-Fritzsch idea are true. In the standard model, it is thought that contributions to the masses of both leptons and quarks arise from electroweak interactions. The masses of the quarks, but not the leptons, would also receive contributions from the strong interactions. Since quarks are confined inside nucleons and mesons, and are not observed as free particles, an exact measurement of their masses is not available. In particle physics, the *current quark mass* is a term used for the mass the quarks would have in the high-energy limit, in which limit they would not be hindered by their interactions with clouds of virtual particles in their environment. One cannot go to the laboratory and change the strength of the nuclear force. However, one can observe what happens with particle accelerators for various beam energies. At different beam energies, experiment shows that coupling constants "run," which means they change with energy because of their varying interactions with the clouds of virtual particles surrounding targets they may encounter. This change in coupling constants with energy also means that the effective mass of particles such as quarks should change with energy. Inside a nucleon, the three valence quarks are not at high energy, hence they have a somewhat higher effective mass called the *constituent quark mass*. The current quark masses, in energy units, of the up and down quarks are thought to be about 3 MeV and 7 MeV, respectively, while their constituent quark masses are thought to be about 315 MeV and 318 MeV, respectively. By comparison, the mass-energy of the top quark is very large, at 174 GeV [*Liss and Tipton*, 1997]. Thus, it seems that the strong force should have some influence on the masses of nucleons and nuclei, although how much seems to be model-dependent and/or uncertain at present.

11. The Conserved Vector Current (CVC) Hypothesis

When we bind protons and neutrons together into a complex nucleus, the charge on the complex nucleus is exactly Z times that of an isolated proton. In fact, the coupling constant e is the same for all particles which have electric charge. No matter what the environment is, whether surrounded by clouds of virtual pions or whatever, the value of this coupling constant does not appear to be disturbed. Of course the distribution of charge is disturbed, so that scattering of high energy beams off a nucleus depends on the actual distribution of the nucleons. However, the coupling in the low energy limit, which is what we call the electric charge, is not changed. We could say then that the charge of a nucleon is not renormalized when it is included in a nucleus.

In a similar way, the conserved vector current hypothesis [*Feynman and Gell-Mann*, 1958; *Feynman*, 1960; *Wilkinson*, 1978] asserts that there is a part of the weak interaction, the so-called vector interaction, whose coupling constant does not depend on whether the nucleon is free or bound in a nucleus. Also, the coupling constant is the same for a muon as for a nucleon. In other words, for low-energy transitions, β-decays proceeding by the vector interaction channel are unchanged by the interaction of pions and nucleons. On the other hand, there is another coupling constant involved in β-decays, the so-called axial vector interactions, which is renormalized by a factor of 1.2 for nucleons in nuclei.

This all has a consequence if the strength of the strong nuclear force changes. The constancy of electric charge means that, to the first approximation, changing the coupling constant for the strong nuclear force will not change the electronic orbitals of atoms, and the everyday chemistry of life could be unaffected by accelerated decay episodes that involve the strong force changing but not the electric force. Would a change in the strength of the strong nuclear force change the rates of β-decays? The CVC hypothesis would indicate that the vector part of the coupling constant is not changed, however, in β-decay the decay rate depends on the size of the energy release (the so-called Q-value). Hence, the rates of β-decays are changed by changes in the strong force.

12. Forbidden Decays and Radioisotope Dating

Beta-minus decay, according to modern ideas, proceeds when one of the down quarks which make up a neutron emits a W^- particle. The down quark is thereby changed into an up quark, which also changes the neutron into a proton. Since the rest energy of the W^- particle is 80 GeV, which is more than the available energy, the W^- is a virtual particle and cannot escape but decays into an electron and an antineutrino. *Chaffin et al.* [2004] proposed that the process can be modeled as a tunneling of the system through an 80 GeV potential barrier. This is similar to the modeling of pair production as a tunneling which was proposed long ago by *Schwinger* [1951] and developed further by *Brezin and Itzykson* [1970] and *Casher et al.* [1979]. Slight variations in the strong force or other parameters then could lead to pronounced changes in the β-decay half-life similar to those found by modeling α-decay as a tunneling. In the case of β-decay, however, the dominant decay modes are forbidden decays, a factor not encountered for α-decay.

It seems that radioisotope dating of rocks using β-decay is always done with isotopes which decay via "forbidden decays." Forbidden decays are not impossible ones but they are of much lower probability than "allowed" or "superallowed" decays. The word "forbidden" is here borrowed from its usage in atomic spectroscopy, where a transition between two electronic states of an atom is "allowed" if certain "selection rules" for the changes in the quantum numbers n, ℓ, j, μ, m_ℓ, m_s are obeyed, corresponding to so-called electric dipole transitions. However, just because a transition is not allowed does not mean that it never occurs. Higher-order processes such as "magnetic dipole" and "electric quadrupole" transitions may be possible, although at a much reduced rate. In the case of nuclear energy levels, there are selection rules operable in the β-decay transitions which are of interest. For the mathematically inclined it means that the matrix elements involve a different operator, but these matrix elements are small and do not become important unless the normal matrix elements vanish. But in the case of radioisotope dating we are usually using decays of this type because otherwise the half-life would not be very long. Nuclei with "allowed" β-decays invariably have a relatively short half-life and hence are not often used in radioisotope dating. A second factor is that the decay energy is usually small for decays of this type. Some examples are:

- ^{40}K: 3rd forbidden transition for the β^- transition (89.33%), decay energy 1.3 MeV

- ^{87}Rb: 2nd forbidden transition, decay energy 0.275 MeV
- ^{187}Re: 1st forbidden transition with a large atomic number $Z=75$, and small decay energy 0.0026 MeV
- ^{176}Lu: 1st forbidden transition, decay energy = 0.57 MeV,
- ^{14}C: allowed transition, decay energy = 0.156 MeV
- ^{10}Be: 2nd forbidden transition, decay energy 0.556 MeV.

It might be pointed out that allowed decays of short half-life typically have decay energies of several MeV, unlike those listed above. The small values of the decay energies also contribute to the sensitivity of the isotope half-lives to changes in nuclear parameters.

In the 1940s, before the theory was very well developed, the classification of transitions as "2nd forbidden," "allowed," etc. was usually done on an empirical basis, by looking at various graphs involving so-called "ft values" [*Konopinski and Uhlenbeck*, 1935, 1941; *Konopinski*, 1943; *Alburger*, 1950; *Brodzinski and Conway*, 1965; *Berenyi*, 1968; *Sastry*, 1969]. Back then, ^{14}C was thought to be a forbidden transition, but now we know that it is an allowed transition with a nuclear spin change of +1 and no parity change. On the time scale of interest here, the half-life of ^{14}C is also relatively short, at 5715 years [*Parrington et al.*, 1996].

The theory of forbidden β-decays is discussed in nuclear physics textbooks, or in sources such as *Konopinski* [1943] or *Behrens and Bühring* [1982]. In the limit of small decay energy Δ, the fraction of all the radioactive atoms decaying per unit time, called the decay constant, is given by:

$$\lambda = \frac{0.693}{T_{1/2}} = \begin{cases} G_F^2 K \Delta^{L+3}, \; for \;\; Z \; small \\ G_F^2 K \Delta^{2+\left(1-\alpha^2 Z^2\right)^{1/2}} \;, Z \; not \; small \end{cases} \tag{9}$$

Here G_F is the Fermi constant, K is a constant, Z is the atomic number, λ is the decay constant, and L is the degree of "forbiddenness" of the decay. Notice that the degree of "forbiddenness" appears in an exponent, so that highly forbidden decays are very sensitive to the values of the decay energies Δ, particularly when Δ is small. Defining p as the exponent that occurs as the power of Δ in equation (9) above, *Dyson*

[1967, 1972] defined a "sensitivity" of the decay constant to changes in the fine-structure constant as shown in Table 2. We are here not interested in variations in the fine-structure constant but in variations in the strong coupling constant. However, since the changes caused by either one are considered to enter through changes in Δ, the sensitivities are very similar.

Table 2. Sensitivity of various forbidden β-decays to changes in decay energy (after *Dyson*, [1972]).

Nucleus	Half-life (years)	Δ (MeV)	*p*	*u*	Sensitivity
^{40}K	1.30×10^{9}	1.31	6	-5	-30
^{87}Rb	5.00×10^{10}	0.275	5	-36	-180
^{123}Te	1.23×10^{13}	0.06(EC)	6	210	1260
^{187}Re	4.00×10^{10}	0.0025	2.8	-6400	-18000

In the theory of β-decay, there is a quantity called the "Weinberg angle" named after a Nobel Prize winner [*Behrens and Bühring*, 1982]. In more recent discussions it is just called "the weak mixing angle," since it was actually Glashow who introduced it, not Weinberg. It measures a mixing between the weak coupling and the electromagnetic coupling. Due to this mixing, it would be very difficult to formulate a successful theory in which the weak coupling constant could change but not the charge of the electron, at least for post-Creation week accelerated decay episodes. Hence, Noah's body could be negatively affected by such a change, if it were large enough. In the standard theory for the Fermi constant, the electroweak equations involve coupling constants g and g' which cancel out of the expression for the Fermi constant [*Kimberly and Magueijo*, 2004]. However, they do not cancel out of the expressions for the electronic charge, as Kimberly and Magueijo showed. Hence, if the Fermi constant is to vary in a realistic manner, models such as those considered above in Section 9 involving Kaluza-Klein excitations or technicolor are needed .

A possible better alternative is to allow large changes in the strong coupling constant, the one which has the biggest influence on the nuclear force and nuclear masses. This coupling is effectively decoupled from the others at the low energies of ordinary life. Also, a change in the strong coupling would not just change α-decay and spontaneous fission, but also the β-decays. According to equation (9) above, the half-life for β-minus decay depends on the decay energy Δ raised to some power. That power is approximately the degree of forbiddenness plus three, at least for nuclei lighter than about those with a proton number $Z=50$. Small changes in the decay energy, caused by small changes in the strong coupling constant, could thus cause relatively large changes in half-life for these forbidden decays.

Potassium-Ar dating depends primarily on the β-minus decay to ^{40}Ca to remove the ^{40}K. That decay involves a spin change of -4 with a parity change, and is third forbidden. Rubidium-Sr decay on the other hand is a spin change of +3 with a parity change, a second forbidden transition. The powers of the decay energy involved are therefore different, since one is third forbidden while the other is second forbidden. This should help explain the differences between K-Ar results and Rb-Sr results which Austin and Snelling have been finding [*Austin and Snelling*, 1998; *Snelling et al.*, 2003; *Snelling*, 2003a, b; *Austin*, 2005; *Snelling*, 2005a, b].

Furthermore, the mathematics shows that Re-Os decays should be the most sensitive of all to accelerated decay, by a factor of about 100 over Rb-Sr and 600 over K-Ar (see Table 2). However, samples suitable for Re-Os dating appear to be less common than for other techniques.

13. Using Double β-Decay Data to Test for Variability of the Fermi Constant

Double β-decay was first studied from a theoretical standpoint by *Goeppert-Mayer* [1935]. Important information can be extracted from the study of this rare type of decay. Not only can it be used to check whether the Fermi constant G_F varies with time, but has some interesting ties to some other questions [*Levi*, 1987].

Ordinary β-minus decay is proportional to the Fermi constant squared.

Double β-decay is a higher order process in which two electrons are emitted in the same decay (not just two β-decays in succession), and has a probability proportional to the fourth power of the Fermi constant [*Barabash*, 1998]. Two neutrinos may be emitted in double β-decay, but it has been proposed that a rarer form of double β-decay occurs in which no neutrinos are emitted may also exist. Since this form of β-decay is rarer, we will not discuss it further here. A double β-decay is not just two β-decays in succession. For example, Figure 14 shows the level scheme for double β-decay of ^{130}Te. A single β-decay cannot occur since the ground state of ^{130}I is higher in energy than that of ^{130}Te. However, double β-decay occurs since the ground state of ^{130}Xe is lower than that of the other two.

The only useful isotope for which the half-life for double β-decay has been directly measured is ^{82}Se. Tellurium-130 and ^{128}Te, have been measured by inferring the half-life from measuring the decay products in geological samples, but the half-life is too long for direct measurement in the laboratory, at least so far. The double β-decay half-life of ^{116}Cd has been measured as $(3.75 \pm 0.35(\text{stat.}) \pm 0.21(\text{syst.})) \times 10^{19}$ years, but geochemical measurements have not been successful [*Arnold et al.*, 1996]. Similar situations exist for ^{100}Mo and ^{76}Ge [*Dassié et al.*, 1995; *Günther et al.*, 1997]. According to *Kirsten* [1983] “only double β-decays leading to rare gas isotopes are accessible to the ‘geochemical’ method.”

A useful laboratory for fundamental research on double β-decay has turned out to be the Fréjus Underground Laboratory. It was constructed in 1980, to perform an experiment for detecting the decay of the proton. At the time the **SU**(5) theory said that the half-life of the proton might be

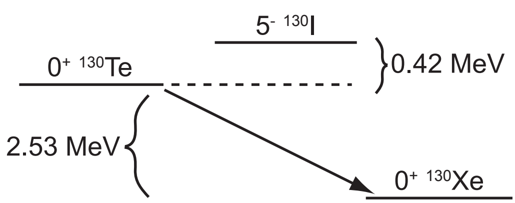


Figure 14. The double-β-decay scheme of ^{130}Te.

10^{29} years. When the proton proved to be stable to the available accuracy, the research activities were expanded to include other projects. Fréjus Underground Laboratory is located at approximately 1700 m under the top of Fréjus mountain, in the medium of the road tunnel of the same name, which eases travel between France and Italy. The about 1600 m of solid rock provided by the Fréjus mountain reduces the cosmic ray background by more than six orders of magnitude (1/2,000,000) compared to the intensity at the earth's surface. Various shields of paraffin, lead, and copper are used to reduce radioactive emissions coming from surrounding rocks and building materials. Thus far, double β-decay observations for ^{100}Mo, ^{76}Ge, ^{82}Se, ^{116}Cd, ^{130}Te, ^{96}Zr, ^{48}Ca, and ^{150}Nd have been planned or already completed.

In 1998, the NEMO (an acronym for Neutrino Ettore Majorana Observatory—named after the physicist Ettore Majorana) collaboration of about 50 French, Russian, Finnish, and American scientists used the Fréjus Underground Laboratory to measure the double β-decay half-life of ^{82}Se, reporting $T_{½}=(0.83\pm0.10(\text{stat.})\pm0.07(\text{syst.}))\times10^{20}$ years [*Arnold et al.*, 1998]. This agrees with an earlier, but less accurate, measurement at University of California, Irvine, which gave $T_{½}=(1.1^{+0.8}_{-0.3})\times10^{20}$ years [*Elliott et al.*, 1987].

With these results, it is possible to compare geochemical data to see if accelerated decay is indicated. If the Fermi constant G_F is changing, then the half-life for double β-decay should change relative to that for ordinary β-decay. Hence, what is needed is a suite of samples for which ^{82}Se and its decay product ^{82}Kr have been measured, and also some other measurements such as K/Ar or Rb/Sr have been performed.

At a 1986 conference in Osaka, Japan, *Kirsten et al.* [1986] reported K/Ar and ^{82}Se/^{82}Kr measurements for various geological samples, Precambrian samples from Boliden, Sweden (Revesund), late Cretaceous or early Tertiary samples from Pakajaka, Bolivia, and some described as Variscan Orogeny from Bukov and Rozna, western Moravia, a region of Czechoslovakia. The Varsican Orogeny was the late Paleozoic (Carboniferous through Permian) mountain-building event in Europe. It appears to correspond with the "Appalachian Orogeny" in eastern North America. In a 1983 American Institute of Physics conference volume, *Kirsten* [1983] also gave some useful data for some clausthalite from Paleozoic rocks from Cacheuta, Argentina. In these samples, the K concentrations are very small, of the order of parts per million, but nevertheless measurable.

Using the raw data, given in the paper by *Kirsten et al.* [1986], model ages for K/Ar can be calculated along with model ages using double β-decay of ^{82}Se to ^{82}Kr. Assuming that contaminant ^{36}Ar is 0.337% of all Ar, and ^{40}Ar is 99.6%, we may find the amount of ^{40}Ar* for each sample. Assuming ^{84}Kr is 56.9% of all "normal" Kr, and 11.56% is ^{82}Kr, we may similarly subtract out the non-radiogenic Kr. Then by dividing (radiogenic ^{82}Kr/^{82}Se) by (^{40}Ar*/^{40}K) we get the dimensionless ratios *R* shown in the Table 3 for each sample.

Table 3. Data on the ratios *R* for each sample.

Sample	*R*
Moravian Be-Bu 1	$(6.47\pm7.41)\times10^{-8}$
Moravian Be-Bu 2	$(13.84\pm15.36)\times10^{-8}$
Moravian Be-Ro	$(11.47\pm13.62)\times10^{-8}$
Bolivian Bl-Pa	$(10.32\pm26.3)\times10^{-8}$
Swedish Sk-Bo a	$(3.40\pm1.27)\times10^{-10}$
Swedish Sk-Bo b	$(9.32\pm4.05)\times10^{-10}$
Argentine clausthalite	$(0.948\pm0.846)\times10^{-10}$

Assuming the NEMO collaboration's value for the ^{82}Se half-life, the 1.277×10^9 year half-life for ^{40}K, and that 10.67% of ^{40}K decays produce ^{40}Ar instead of ^{40}Ca, we may plot what the ratio *R* should look like as a function of time. This graph is shown Figure 15.

The time axis units are billions of years. Thus "20" means 20×10^8 years or 2 billion years. All of the samples except the Swedish, and possibly the Argentine samples, have unacceptable limits of error, causing the *R* value to come out on a scale of 10^{-7}, but with the error bars bracketing a value of the order of 100% to 200%. However, the error bars for the Swedish samples were smaller, the $(3.40\pm1.27)\times10^{-10}$ value giving results consistent with an age between 1.54 and 5.5 billion years.

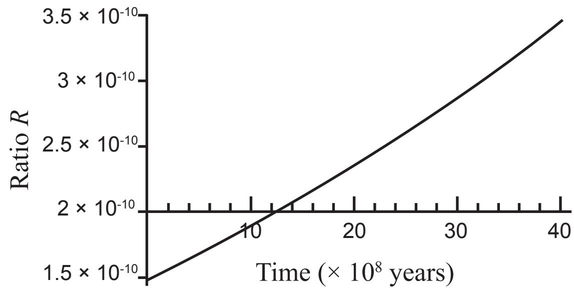


Figure 15. The ratio R of (radiogenic ^{82}Kr/^{82}Se) divided by (^{40}Ar*/^{40}K) versus time.

Precambrian rocks of Boliden, central Sweden, give their name to an ore formation located there. The Revesund Granite is found there and over a large area of central Sweden. It is assigned a uniformitarian age of 1.75 billion years. The data for the Swedish Boliden rocks are interesting in that the above R value derived from the data indicate a somewhat older age for the formations than the uniformitarian age of 1.75 billion years for these Precambrian rocks. Does this show whether the Fermi constant varied over time? *Barabash* [1998, 2000, 2003, 2004] interpreted the data as indicating such a variation. However, his analysis of the geochemical data assumed that the uniformitarian geologic timetable is correct. If the Boliden rocks are supposed to be 1.75×10^9 years old, then the mean R ratio of 3.40×10^{-10} is too big according to Figure 15, possibly indicating accelerated decay had to occur to produce this large value of R. This shows that this method has promise, but more accuracy is needed. Perhaps more data will appear in the literature which would make better determinations possible and show whether accelerated decay occurred in this way. The NEMO-3 detector is now operating, and may produce a laboratory result for ^{130}Te. This would then enable the large body of geochemical data that exist in the literature for ^{130}Te to be compared with present-day laboratory results. If the Fermi constant is not varying, but the strong interaction coupling did vary, these analyses should help show that this is the case. If both vary, these data should still be valuable to sort out the mechanisms that are responsible.

14. Conclusion

Because God is the Creator of physical principles, it would be wrong to state that He must act in a certain way. However, Scripture is a reliable record of His actual Creation. The models considered here merely point out some unnecessary assumptions involved in interpreting radioactive decay: half-lives may not have been constant.

In our studies of α-decay, it is found that small changes in the strength of the nuclear force can lead to large changes in the half-life of a nucleus such as U^{238}. Using realistic values for the strength and range for the nuclear force it was found that a small change in the depth of the nuclear potential well can cause a change in the number of nodes in the α-particle wavefunction, resulting in a change in the half-life that in some cases could be as much as a factor of 10^8.

It was found that these models are consistent with the U isotope distributions found in nature, and their approach to radioactive equilibrium. These results enable one to conjecture about how much the variation in nuclear force must have been in order to explain present-day isotopic abundances. Since there is no precise number to match with theory, and since various approaches to the final, present-day abundances are possible, these results remain exploratory in nature. In the case of the Oklo natural reactors, a study of the resonance absorption of neutrons by ^{149}Sm was found to place some constraints on the time during earth history when the reactions could have occurred, and/or the type of model that is consistent with the data.

Borrowing some ideas from Kaluza-Klein theory and string theory, we found that changes in the radii of compact extra dimensions can lead to a change in the effective coupling constant for the strong force, hence in the strength of the nuclear force. Although extended Kaluza-Klein and string theories must be considered as highly tentative theories, in this work we find some explicit equations showing the possible variation of the strong and weak coupling constants. We discussed the connection between coupling constants and the sizes of the holes in a Calabi-Yau shape. We also discussed modern unified theories of the strong, weak and electromagnetic forces and the implications of changes in coupling constants and Yukawa couplings as far as the effect on particle masses is concerned. We conclude that, although all the relevant measurements and theories are not yet available, consistent theories which allow accelerated decay seem to be possible. It seems that the best models, the ones which would be most likely to be successful, would involve a variation in the strong force rather than the electromagnetic force. Whether the weak force can vary in a way consistent with observation seems doubtful.

We discussed the idea of a forbidden transition in β-decay theory, and found that most of the nuclei that are of interest in radioisotope dating problems undergo forbidden transitions with a comparatively small decay energy (the Q-value). The sensitivity of a theoretical value of the half-life of a β-decay was found to be increased by a smallness of the relevant Q-value. A change in the strong force could therefore affect the β-decays of these nuclei through change in the Q-value.

Double β-decay promises to provide a check on whether accelerated decay has occurred. The double β-decay of ^{82}Se already gives some evidence of this type, but more data will possibly become available in the next few years if direct measurements of the half-life of ^{130}Te are successful. Perhaps future studies will be able to connect more precisely with the data.

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