Cosmology and the Radioactive Decay Ages of Terrestrial Rocks and Meteorites*

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Several different cosmologies have been proposed in which the strength of the gravitational interaction is variable. Also, it has been suggested that the gravitational interaction may play a significant role in determining the structure of elementary particles, and in particular that the value of the fine structure constant may depend on the strength of the gravitational interaction. It is shown that these two effects taken together would lead to observable discrepancies in the ages of terrestrial rocks and meteorites as determined by different radioactive decay schemes. Analysis of the geophysical data leads to an upper limit of about 3 parts in 10^{13} per year on the rate of change of the fine structure constant. If the assumed relation between gravitation and particle structure were valid, this would correspond to a limit on variations in the strength of the gravitational interaction of 2 parts in 10^{11} per year. This upper limit is one-fifth of the size of the variations expected according to Dirac's cosmology, and roughly as big as the variation to be expected according to the Brans-Dicke cosmology. It is concluded that either the assumed connection between gravitation and elementary particles does not exist, or, if the connection does exist, that the geophysical data provide a significant limit on possible variations in the strength of the gravitational interaction.

1. INTRODUCTION

In recent years, there has been some discussion of cosmologies in which the strength of the gravitational interaction is variable.[1–5] It has also been suggested that the weak-interaction coupling constant (hence β-decay rates) may be variable.[6] Another possibility is that the strength of the electrical interactions, which is given by the fine structure constant, may be variable[4] or that particle mass ratios may not be fixed. It is the purpose of this article to show that the geophysical data on the ages of terrestrial rocks and meteorites, as determined by radioactive decay schemes, are of significance for these theories, particularly as they relate to the weak and electromagnetic coupling constants.

The possible connection between the gravitational interaction and radioactive decay ages is provided by the following idea, which has been discussed by Arnowitt, Deser, and Misner.[7] We suppose that the charge e of an elementary particle is confined to a region of space with dimensions of the order of

$$Ge^{1/2}/c^2 \sim 10^{-34} \text{ cm}. \tag{1}$$

Here G is the gravitational constant. By the observed equivalence between energy and gravitational mass, the gravitational force which tends to hold this charge distribution together is expected to be of the same order of magnitude as the electric forces in the system. The region of space around the system suffers very large curvature, and this curvature cannot be neglected in discussing the structure of the system. Landau[8] suggested that this effect may lead to a cutoff in the virtual quanta of the field associated with a charged elementary particle. Landau showed that if the unrenormalized fine structure constant α_0 satisfied the condition $\alpha_0 \ll 1$, the renormalized fine structure constant $\alpha = e^2/\hbar c$ would be given by the approximate equation

$$\alpha = \frac{\alpha_0}{1+(\alpha_0\nu/3\pi)\ln(\Lambda^2/m^2)}, \tag{2}$$

where m is the mass of an elementary particle, and Λ is the cutoff mass. The number ν depends on the number and kinds (whether spin 0 or spin 1/2) of different charged elementary particles. Landau suggested that $\nu \sim 12$. If the cutoff length were equal to the length (1), then $\ln(\Lambda^2/m^2) \sim 10^2$, and it would be interesting to consider the assumption $\alpha_0 \ln(\Lambda^2/m^2) \gg 1$. In this case, α would be given by the approximate equation

$$\alpha^{-1} \cong \frac{\nu}{3\pi} \ln\frac{\hbar c}{Gm^2}, \tag{3}$$

where $Gm^2/\hbar c$ is the dimensionless number, of the order of 10^{-40}, which characterizes the strength of the gravitational interaction.

According to the above idea, the gravitational interaction may play an important role in the structure of the elementary particles. Thus, it is of interest for cosmologies with a variable gravitational constant to see if the properties of the elementary particles, such as charge and mass, may be variable.

If the masses or charges of elementary particles changed with time, the decay rates of atomic nuclei would be variable, and in general the decay rates of

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[2] D. W. Sciama, Monthly Notices Roy. Astron. Soc. **113**, 34 (1953).
[3] P. Jordan, Z. Physik **157**, 112 (1959); *Schwerkraft und Weltall* (Friedrick Vieweg und Sohn, Braunschweig, Germany, 1955).
[4] R. H. Dicke, Science **129**, 621 (1959).
[5] C. Brans and R. H. Dicke, Phys. Rev. **124**, 925 (1961).
[6] R. H. Dicke, Nature **183**, 170 (1959).
[7] R. Arnowitt, S. Deser, and C. W. Misner, Phys. Rev. **120**, 313 (1960).
[8] L. Landau, in *Niels Bhor and the Development of Physics*, edited by W. Pauli (McGraw-Hill Book Company, New York, 1955).

different nuclei would not vary with time in the same way. This would lead to discrepancies in the ages of a given rock as determined by different radioactive decay schemes. The particular significance of this test is based on the fact that the decay rates of the long-lived isotopes used in geologic dating depend very sensitively on the values of parameters such as the fine structure constant. For example, a long-lived isotope unstable against electron capture or against electron emission would have very small decay energy, so that a small change in the fine structure constant, leading to small changes in the energies of parent and daughter nuclei, may cause a very significant change in the decay energy, and hence in the decay rate.

In the discussion of the geophysical data, it is assumed that the strength $Gm^2/\hbar c$ of the gravitational interaction is decreasing approximately uniformly with time. It has been suggested from a comparison of the observed stellar and galactic evolutionary ages with the Hubble age and the uranium-lead age of the elements that $Gm^2/\hbar c$ may be decreasing at a rate of about one to three parts in 10^{11} per year.[9] This is based on a generally covariant gravity theory[5] of the Jordan type.[3] Dirac[1] suggested that the strength of the gravitational interaction might be inversely proportional to the age of the universe. This would mean that $Gm^2/\hbar c$ is decreasing presently at the rate of about one part in 10^{10} per year, assuming that the age of the universe is 2/3 of the Hubble age, and that the Hubble age is about 15 billion yr, slightly larger than the accepted value.

It is assumed that the value of the fine structure constant is variable, being given by Eq. (3). For simplicity, it is assumed that the values of other physical numbers, such as ratios of masses of elementary particles, and the strong and weak coupling constants, are constant. The consequences for a more general, and perhaps more realistic assumption are not considered here.

The variations with time in the decay rates, expressed in atomic time units ($\hbar/mc^2$), of the various isotopes used in geologic dating are computed in Sec. 2. In Sec. 3 the available data, consisting of the laboratory observations of decay rates, terrestrial rock age determinations, and the observed ages of meteorites, are used to find an upper limit on the possible variation in the fine structure constant.

2. CALCULATION OF THE VARIATIONS IN DECAY RATES

It is convenient to use units such that $\hbar$ and c are constant, and the masses of the elementary particles are constant. If the decay rate (expressed in these units) of an isotope were variable, the age of a rock which one would determine in the usual way from the amounts of parent and radiogenic daughter isotopes in the rock, and from the laboratory value of the decay rate, would be different from the age of the rock measured in units of $\hbar/mc^2$. We shall call the age inferred from the geological data (that is, on the assumption of constant decay rate) the apparent age, t^*. It is easy to see that the apparent age is related to the atomic age t by the equation

$$t^*(t)=\frac{1}{\lambda(t)}\int_0^t \lambda(t')dt', \tag{4}$$

where $\lambda(t')$ is the decay rate at time t', and $\lambda(t)$ is the laboratory value (present value) of the decay rate.

We consider first the effect of variable fine structure constant on nuclear beta-decay rates. Approximate equations are given first for the variation of decay energy with α, and then for the variation of decay rate with decay energy.

If the numerical value of the fine structure constant were to change from α to $\alpha+\delta\alpha$, the change δE in the energy of a nucleus would be composed of the change in the contribution to the energy of the nucleus by the electromagnetic forces, plus the change in all other energy (meson interaction energy, kinetic energy of the nucleons). The change in the electrostatic energy of the nucleus depends directly on $\delta\alpha/\alpha$, and also on the change in the size of the nucleus. It may be verified from estimates[10] of the compressibility of nuclear matter that for the magnitude of $\delta\alpha/\alpha$ contemplated ($\delta\alpha/\alpha\lesssim 10^{-3}$) the effects associated with the change in nuclear radius are negligible. (By the stability condition, the energy is independent of small departures of the radius from the equilibrium value.) The change in the energy of the nucleus is given to excellent accuracy by the equation

$$\delta E=E_c\delta\alpha/\alpha, \tag{5}$$

where E_c is the electrostatic energy of the nucleus. That is, consequent on a change $\delta\alpha$ in the strength of the electromagnetic interaction the end-point energy changes by the amount

$$\text{Change in decay energy}=\Delta E_c\delta\alpha/\alpha, \tag{6}$$

where ΔE_c is the difference between the electrostatic energy of the parent nucleus and the electrostatic energy of the daughter nucleus.

Assuming the approximate formula for the electrostatic energy of a nucleus with atomic number Z and atomic weight A,

$$E_c=0.6Z(Z-1)e^2/r_0A^{1/3}, \tag{7}$$

with $r_0=1.2\times10^{-13}$ cm, the electrostatic energy difference between parent and daughter nuclei is

$$\Delta E_c\cong 1.2Ze^2/r_0A^{1/3}. \tag{8}$$

It should be noted that the actual value of the electrostatic energy difference may be quite different from

[9] R. H. Dicke, Revs. Modern Phys. **34**, 110 (1962).

[10] K. A. Brueckner, Revs. Modern Phys. **30**, 561 (1958).

that given by Eq. (8) because the charge radii of parent and daughter nuclei may differ from the approximate value $r_0A^{1/3}$.

Since we are interested in very long-lived isotopes, where the decay energy is small, the nonrelativistic approximation is adequate. Using the standard method,[11] it is easy to see that the rate λ_β for electron emission depends on the end-point energy E according to the approximate equation

$$\lambda_\beta = C_\beta E^{l+3}, \tag{9}$$

where C_β is substantially independent of α, and l is the degree of forbiddenness of the transition. The rate λ_{ec} for nuclear electron capture is

$$\lambda_{ec} = C_{ec} E^{2l+2}, \tag{10}$$

where again C_{ec} is not a sensitive function of α, E is the decay energy, and l is the degree of forbiddenness of the transition.

The electron capture or electron emission rate as a function of time may be computed in terms of the present value of the decay rate, using Eq. (6) for variations in the decay energy, Eq. (8) for the electrostatic energy difference between parent and daughter nuclei, and Eq. (9) or (10).

For nuclear alpha decay, it is adequate to use the equation for the decay rate in JWKB approximation,

$$\lambda = C \exp\left(-\int_R^{r_0} 2\kappa dr\right), \tag{11}$$

where

$$\kappa^2 = \frac{4Ze^2M}{\hbar^2}\left(\frac{1}{r} - \frac{1}{r_0}\right), \tag{12}$$

and

$$r_0 = 2Ze^2/\epsilon.$$

We have neglected the centrifugal barrier. The term C may be taken to be independent of α. The channel radius for alpha decay is R, M is the mass of an alpha particle, Ze is the charge of the daughter nucleus, and ϵ is the alpha-decay energy.

Using these equations we find that the nuclear alpha-decay rate $\lambda(\alpha+\delta\alpha)$ when the value of the fine structure constant is $\alpha+\delta\alpha$ is related to the rate $\lambda(\alpha)$ when the fine structure constant is α by the equation

$$\lambda(\alpha+\delta\alpha) = \lambda(\alpha) \exp\left\{2Z\alpha\left(\frac{2Mc^2}{\epsilon}\right)^{1/2} \frac{\delta\alpha}{\alpha} g\left(\frac{2Ze^2}{\epsilon R}\right)\right\},$$

$$g(x) = (x-1)^{1/2} + (x-2)\cos^{-1}(x^{-1/2}). \tag{13}$$

The equations given in this section, with Eq. (3), are used to calculate the apparent age of a rock (the age evaluated on the assumption of constant decay rate) as a function of the age of the rock measured in atomic time units. The apparent ages are listed in Table I for the various decay schemes commonly used in geologic dating.

TABLE I. Apparent radioactive decay ages. The ages in a column of the table list, for a given rock, the radioactive decay ages which would be expected, assuming Eq. (3), for various assumptions about the rate of decrease in the gravitational constant. The first age in each column is the "true" age of the rock, measured in atomic units, $\hbar/mc^2$. The ages are given as multiples of one billion years.

Fractional decrease in G per year	K^{40}/Ar^{40} method			Rb^{87}/Sr^{87} method			U/Pb method		
0	2.0	4.0	5.0	2.0	4.0	5.0	2.0	4.0	5.0
1×10^{-11}	2.06	4.18	5.25	1.96	3.84	4.76	2.06	4.25	5.40
2.5×10^{-11}	2.20	4.51	5.69	1.89	3.58	4.34	2.17	4.68	6.10
5×10^{-11}	2.34	5.16	6.67	1.78	3.16	3.70	2.36	5.69	7.89

The decay energy for the decay of K^{40} to Ar^{40} by electron capture was taken to be 60 keV,[12] and it was assumed that the transition is to a state with spin equal to two, and even parity (first forbidden transition). There is some evidence (from the ratio of K to L electron capture rates) either that the decay energy is smaller than 60 keV, or that the spin and parity assignments of the daughter state are not correct.[12] If the decay energy were smaller, or if the decay were more highly forbidden, the decay rate would change more rapidly with changes in the fine structure constant.

Equation (8) for the electrostatic energy difference between parent and daughter nuclei may not be valid if there are significant departures from the simple formula for the nuclear radius. Such departures are to be expected near closed nuclear shells. It may be significant that K^{40} has 19 protons, one less than a closed shell for protons, while Rb^{87} has 50 neutrons, a closed shell for neutrons. If the Coulomb energy differences between parent and daughter nuclei were fortuitously small, the expected discrepancies listed in Table I would be reduced.

3. ANALYSIS OF THE GEOPHYSICAL DATA

Laboratory determinations of the decay rates of K^{40} and Rb^{87} are listed in Sec. A. These decay rates have been determined also by comparisons of the ages of terrestrial rocks as found by different decay schemes, the ages of the rocks ranging from about 100 million yr to 2.5 billion yr. The determinations are given in Sec. B. Finally, the data on meteorites are listed in Sec. C. An analysis of the data is given in Sec. D. In Sec. E, the decay of Re^{187} is separately considered. This decay is of interest because the decay energy is very small, so that it may afford a particularly good test of the assumption of variable α.

[11] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[12] R. E. Holland and J. F. Lynch, Phys. Rev. **113**, 903 (1959).

A. Laboratory Determinations of Decay Rates

Rb^{87} decays to Sr^{87} by electron emission. The end-point energy is fairly small—270 keV—and since the decay is forbidden, the emission of electrons with small momentum is favored. This means that a reliable laboratory determination of the decay rate is not straightforward. Flynn and Glendenin[13] found the value

$$\lambda=(1.47\pm0.03)\times10^{-11}(\mathrm{yr})^{-1} \tag{14}$$

for the decay rate of Rb^{87}, while Libby[14] gives the value

$$\lambda=(1.41\pm0.06)\times10^{-11}(\mathrm{yr})^{-1}. \tag{15}$$

However, Egelkraut and Leutz[15] recently have obtained

$$\lambda=(1.19\pm0.02)\times10^{-11}(\mathrm{yr})^{-1}. \tag{16}$$

K^{40} decays to Ca^{40} by electron emission, and to Ar^{40} by electron capture. It is the latter branch which has been used extensively in radioactive dating. The latest laboratory value for the electron emission rate is[16]

$$\lambda_\beta=(4.72\pm0.09)\times10^{-10}(\mathrm{yr})^{-1}. \tag{17}$$

The ratio of electron capture to electron emission rate in K^{40} was found to be

$$\lambda_e/\lambda_\beta=0.124\pm0.002 \tag{18}$$

by McNair *et al.*[17]

B. Terrestrial Rock Data

Aldrich *et al.*[18] compared rubidium-strontium ages with uranium-lead ages for six different minerals having concordant uranium-lead ages running from 400 million yr to 2.5 billion yr. They concluded that the decay rate of Rb^{87} is

$$\lambda=(1.39\pm0.6)\times10^{-11}(\mathrm{yr})^{-1}. \tag{19}$$

This is 5% smaller than the laboratory determination by Flynn and Glendenin [Eq. (14)].

Wetherill *et al.*[19] determined the decay parameters of K^{40} by comparisons of potassium-argon ages and concordant uranium-lead ages of terrestrial rocks, and one meteorite. The electron capture rate was found from data on very young rocks to be

$$\lambda_{ec}=5.57\times10^{-11}(\mathrm{yr})^{-1}. \tag{20}$$

Assuming this value, the electron emission rate was found from six rocks with ages ranging from 1 to 2.5 billion yr, and one meteorite, to be

$$\lambda_\beta=4.72\times10^{-10}(\mathrm{yr})^{-1}. \tag{21}$$

This value is consistent with the laboratory observations [Eq. (17)]. The ratio of electron capture to electron emission rates is 0.117, 5% smaller than the laboratory determination.

TABLE II. Meteorite age determinations.

Method	Age
Pb^{207}/Pb^{206}	4.55±0.07 billion yr.[a] (This age is based on data for three stone meteorites, two iron meteorites.)
	4.6±0.05 billion yr[b] (based on five different chondritic meteorites)
K^{40}/Ar^{40}	4.00 to 4.40±0.1 billion yr[c] (based on seven different chondritic meteorites)
	3.3 to 4.25±0.2 billion yr[d] (based on five different chondritic meteorites)
Rb^{87}/Sr^{87}	4.37±0.1 billion yr[e] (based on four achondritic meteorites and four chondritic meteorites)

[a] See reference 26.
[b] See reference 27. The error here is the internal error estimated from nine lead-lead age determinations.
[c] See reference 24.
[d] See reference 25.
[e] See reference 21. The error was estimated from the internal error in the Rb/Sr ages of the four chondrites. The decay rate of Rb^{87} was taken to be 1.47×10^{11} per year.

C. Meteorite Data

Ages of the meteorites determined by the lead-lead, potassium-argon, and rubidium-strontium methods are listed in Table II. Measurements of the radioactive decay ages of meteorites have been summarized recently by Anders.[20]

Gast[21] found that the rubidium-strontium age of the meteorites is 4.37 billion yr, with an internal error which may be estimated from the scatter of the data to be very roughly equal to 2%. This age is based on measurements on four different achondrites and four different chondritic meteorites. The decay rate of Rb^{87} was taken to be equal to 1.47×10^{-11} yr^{-1}. The age is derived from the simple model where it is assumed that the isotopic distribution of strontium was the same in the material of all meteorites at some definite time in the past, and that since that time there has been no appreciable mixing of the rubidium and strontium in different meteorite samples. The age is consistent with the earlier rubidium-strontium ages of 4.5±0.4 billion yr[22] and 4.3±0.4 billion yr,[23] both of which are derived from measurements on two different meteorites with different abundances of rubidium relative to strontium.

Since argon may be lost by diffusion from the material of meteorites, the potassium-argon age determinations of meteorites are minimum ages for the time since the parent meteorite body cooled. Geiss and

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[19] G. W. Wetherill, G. J. Wasserburg, L. T. Aldrich, G. R. Tilton, and R. J. Hayden, Phys. Rev. **103**, 987 (1956).
[20] E. A. Anders, Revs. Modern Phys. **34**, 289 (1962).
[21] P. W. Gast (to be published).
[22] V. E. Schumacher, Z. Naturforsch. **11a**, 206 (1956).
[23] R. K. Webster, J. W. Morgan, and A. A. Smales, Trans. Am. Geophys. Union **38**, 543 (1957).

Hess[24] found that the potassium-argon ages of seven different chondritic meteorites lie within the range 4.00 to 4.40 billion yr, with quoted errors of about 2% on the age measurements. Wänke and König[25] found the ages of five different chondrites to be between 3.33 billion yr and 4.25 billion yr. These ages were calculated using the decay parameters $\lambda_{ec}/\lambda_\beta=0.124$ and $\lambda=\lambda_{ec}+\lambda_\beta=5.45\times10^{-10}$ yr^{-1}. If the decay rates determined from the geologic data were used [Eqs. (6) and (7)], the ages would be increased by about 0.2 billion yr.

The age of the meteorites as determined by the ratio of Pb^{207}/Pb^{206} is 4.55 billion yr.[26,27] The error on this number is not expected to be greater than about 1%.

It is concluded that the three different methods for determining the age of the meteorites do not exhibit any manifest inconsistencies. The lead-lead age is 4.55 $\pm$0.05 billion yr. The best value for the rubidium-strontium age is 4.37 million yr, with an internal error of 0.1 billion yr. The quoted error of 2% on the decay rate of Rb^{87} leads to an additional uncertainty of 0.1 billion yr in the age. The largest potassium-argon age is 4.40 billion yr, where the quoted uncertainty in the age is about 0.1 billion yr. Taking account of the uncertainty in decay rates, this error might reasonably be larger, perhaps 0.2 billion yr. It is possible that the potassium-argon age corrected for argon loss might be substantially larger than the lead-lead age and the rubidium-strontium age. However, if all meteorites lost substantial amounts of argon, one probably would expect that different meteorite samples would have lost different amounts of argon, leading to a large spread in the observed potassium-argon ages, and conflicting with the rather consistent potassium-argon ages of chondritic meteorites.[24,25]

D. Upper Limit or Possible Variations in the Fine Structure Constant

If the value of the fine structure constant were variable, the apparent ages of the meteorites, as determined by different decay schemes, would not be consistent. In Table III we have listed the apparent ages of the meteorites assuming that the fine structure constant is decreasing with time. In this table, the lead-lead age of the meteorites was taken to be 4.5 billion yr.

It is apparent from Table III that if G were decreasing by one part in 10^{11} per year, and if Eq. (3) were valid, the rubidium-strontium age of the meteorites should be about 4.0 billion yr. This is 0.37 billion yr smaller than the observed rubidium-strontium age, and comparable with the estimated error in the age of 0.2 billion yr. Since there may well be systematic errors both in the laboratory value of the decay rate of Rb^{87} and in the meteorite data, it is concluded that there is no significant discrepancy between the calculated rubidium-strontium age and the observed age. It should be noted that there are uncertainties in the calculated ages given in Table III. The difference between the electrostatic energies of Rb^{87} and Sr^{87} may be smaller than the value we have assumed [given by Eq. (8)], and in this case the expected discrepancy between the ages would be smaller.

Table III. Calculated radioactive decay ages of the meteorites. In this table the lead-lead age of the meteorites was taken to be 4.5 billion yr. The Rb/Sr and K/Ar ages of the meteorites to be expected on the assumption of variable fine structure constant were drawn from Table I.

Fractional decrease in G per year	Lead-lead age	K/Ar age	Rb/Sr age	True age
1×10^{-11}	4.5	4.4	4.0	4.2
2.5×10^{-11}	4.5	4.3	3.5	3.8
5×10^{-11}	4.5	4.2	2.8	3.3

With G decreasing by one part in 10^{11} per year, the potassium-argon age would be expected to be 0.1 billion yr smaller than the lead-lead age. This is consistent with the observations.

It is concluded that the assumption of variable α [Eq. (3)], with G decreasing by one part in 10^{11} per year, cannot be ruled out by the comparison of meteorite data and the laboratory determinations of decay rates.

The expected discrepancies due to variable α are much smaller in terrestrial rocks than in meteorites, because the meteorites are almost twice as old as the oldest terrestrial rocks. With G decreasing by one part in 10^{11} per year, the rubidium-strontium age of a terrestrial rock which is 2 billion yr old would be, by Table I, 0.1 billion yr smaller than the potassium-argon or uranium-lead age. Uncertainties in the thermal, mechanical, and chemical histories of terrestrial rock samples lead to uncertainties in the age which are at least as large as this discrepancy. (See, for example, the review article by Aldrich and Wetherill.[28]) That is, the terrestrial rock data do not provide as significant a test of the assumption of variable fine structure constant as do the available meteorite data.

If G were decreasing by 2.5 parts in 10^{11} per year, the rubidium-strontium age of the meteorites should be about 3.5 billion yr. The discrepancy between this age and the observed age could not reasonably be attributed to errors in the measurement. One might argue as above that the electrostatic energy difference may have been such as to lead to a fortuitous agreement between the three apparent ages of the meteorites. For example, if the difference between the electrostatic energies of

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[27] D. C. Hess and R. R. Marshall, Geochim. et. Cosmochim. Acta. **20**, 284 (1960).
[28] L. T. Aldrich and G. W. Wetherill, Ann. Rev. Nuclear Sci. **8**, 257 (1958).

Rb^{87} and Sr^{87} were one quarter of the value we have used, the apparent rubidium-strontium age would be almost 4.0 billion yr. If G were decreasing by 5 parts in 10^{11} per year, it would be necessary to assume that the electrostatic energy difference between Rb^{87} and Sr^{87} given by Eq. (8) had the wrong sign. Also, there should be a significant discrepancy between the potassium-argon age and the lead-lead age of the meteorites. It is concluded that a variation in G of 2 parts in 10^{11} per year might not be ruled out, while a variation amounting to 5 parts in 10^{11} per year is very unlikely.

E. Rhenium-Osmium Ages

The decay of Re^{187} to Os^{187} by electron emission may be particularly interesting. The decay energy appears to be so small that the decay can be observed in the laboratory only with great difficulty, if at all. Suttle and Libby[29] found a half-life of 10^{11} yr, and an end-point energy of about 8 keV. Dixon and McNair[30] found no activity, and set an upper limit of 1 keV on the end-point energy. The most recent laboratory results[31] are that the decay energy is about 3 keV, and that the half-life is $(1.2\pm0.4)\times10^{11}$ yr.

If the end-point energy were of the order of 1 keV, the decay rate would be a most sensitive function of α, unless the difference between the electrostatic energies of the parent and daughter nuclei happened to be fortuitously small. If the electrostatic energy difference were given correctly by Eq. (8), a change of one part in 10^4 in the value of the fine structure constant would cause a change of about one keV in the decay energy, that is, a change in decay energy of the same order as the decay energy. If α were decreasing with time, the decay would have gone more slowly in the past, and after a sufficiently large time the direction of the decay would have changed, with Os^{187} unstable against electron capture.

Herr and Merz[32] measured the abundance and isotopic distribution of rhenium and osmium in 18 rhenium-rich rocks. The results provide convincing evidence that Re^{187} has been decaying into Os^{187}. The ages of two of the rocks were found by the uranium-lead method to be 235 million yr and 962 million yr. Using these ages, the authors found that the half-life of Re^{187} is about 6×10^{10} yr. This estimate has been reduced recently to about 4×10^{10} yr,[33] a factor of three smaller than the most recent laboratory result.[31]

It would be of interest to compare the above half-life, which was determined using young rocks, with the half-life determined from very old rocks, or from meteorites. The abundance and isotopic distributions of rhenium and osmium in some stoney meteorites have been measured.[34] Assuming that the age of the meteorites is 4.5 billion yr, the half-life of Re^{187} is estimated from the meteorite data to be 5×10^{10} yr. It should be emphasized that the above estimates of the half-life must be regarded as tentative. For a significant test of the assumption of variable α, it would be necessary to have a reliable laboratory determination of the decay energy of Re^{187}, as well as the geophysical data. It is concluded that this decay may provide a significant limit or possible variations in α, when more data are available.

4. DISCUSSION AND CONCLUSION

We have shown that the value of the fine structure constant almost certainly has not been decreasing by more than about three parts in 10^{13} per year in the past 4.5 billion yr. Assuming Eq. (3), this leads to an upper limit of about two parts in 10^{11} per year on possible variations in the strength of the gravitational interaction. It will be recalled that the gravitational constant is estimated to be decreasing at the rate of one part in 10^{10} per year according to Dirac's cosmology, and at the rate of from one to three parts in 10^{11} per year in the Brans-Dicke cosmology. That is, we must conclude either that the strength of the gravitational interaction is changing more slowly than is indicated by Dirac's cosmology, or that the fine structure constant is not related to G by the approximate Eq. (3).

If the weak interaction coupling constant were decreasing with time, the beta-decay ages, K/Ar and Rb/Sr, would be larger than the lead-lead age. It has been estimated that due to this effect the beta-decay ages of the meteorites would be 0.2 to 0.5 billion yr larger than the lead-lead age.[6] Because of uncertainties in the amount of argon lost by the material of the meteorites, the K/Ar data need not conflict with this idea. The Rb/Sr age of the meteorites is 0.2 billion yr smaller than the lead-lead age, where the error in the age has been estimated to be about 0.2 billion yr. However, since there may well be systematic errors both in the meteorite data and in the decay rate of Rb^{87}, so that the error in the Rb/Sr age might well be as large as 0.4 billion yr, it is not yet reasonable to rule out the idea of a variable weak-interaction coupling constant.

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