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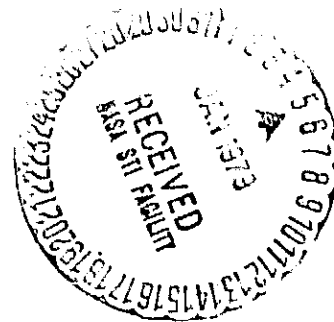
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MEMORANDUM

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AN EXPERIMENT TO VERIFY THAT THE WEAK INTERACTIONS
SATISFY THE STRONG EQUIVALENCE PRINCIPLE

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16. ABSTRACT

    This report proposes the construction of a clock based on the beta decay process to test for any violations by the weak interaction of the strong equivalence principle. The basic idea is to determine whether the weak interaction coupling constant β is spatially constant or whether it is a function of gravitational potential U. The clock will be constructed by simply counting the beta disintegrations of some suitable source. The total number of counts will be taken as a measure of elapsed time. The accuracy of the clock will be limited by the statistical fluctuations in the number of counts N, which is equal to $\sqrt{N}$. Thus, to obtain an accuracy of 1 part in 10^6 one needs a total number of counts of 10^{12}, a feasible number to actually measure in a few weeks' time. Increasing N gives a corresponding increase in accuracy. It is proposed to use a source based on the electron capture process so as to avoid low energy electron discrimination problems. Solid state and gaseous detectors are being considered. While the accuracy of this type of beta decay clock is much less than clocks based on the electromagnetic interaction, there is a corresponding lack of knowledge of the behavior of β as a function of gravitational potential. No predictions from nonmetric theories as to variations in β are available as yet, but they may occur at the U/C^2 level.

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AN EXPERIMENT TO VERIFY THAT THE WEAK INTERACTIONS SATISFY THE STRONG EQUIVALENCE PRINCIPLE

I. SCIENTIFIC BACKGROUND

General Relativity and other metric theories of gravity are constructed so as to incorporate the principle of equivalence. This principle is usually stated in two forms [1]. The Weak Equivalence Principle (WEP) states that test body trajectories are independent of composition, and this is supported experimentally to very high accuracy by recent versions of the Eötvös Experiment [2,3]. The Strong Equivalence Principle (SEP), a much more restrictive statement, states that in any freely falling frame anywhere at any time the laws of physics take on their present special relativistic form. A possible connection between these two statements is the Schiff conjecture [4] which states that any acceptable theory of gravitation which satisfies the WEP must also satisfy the SEP. Schiff's conjecture has not been proven except in a restricted form, and there is an unpublished counter-example by Ni.[1] Metric theories of gravity are able to satisfy the SEP because of the existence of local Lorentz frames and the metric meshing of nongravitational phenomena by the "comma goes to semicolon" rule, and this is the only known way to incorporate SEP in theories of gravitation. If Schiff's conjecture is true, then the high accuracy of the Eötvös experiment (1 part in 10^{11}) can be used as evidence for the necessity of metric theories of gravity.

In the absence of a completely general proof of Schiff's conjecture and with the knowledge that an equally compelling statement known as Mach's principle is at odds with SEP [5], it is of interest to look for new direct experimental tests of SEP. Any search for deviations from the usual laws of physics in freely falling frames with large spatial or temporal separation constitutes a test of SEP. Since it is unlikely that there are discontinuous changes in the equations governing physical processes, the physical constants which appear in these equations have been scrutinized for any possible continuous changes [6].

Changes in the gravitational constant G with time have been proposed by Dirac [7] and Dicke [8]. Dirac was motivated by a desire to explain the large number coincidences of cosmology, and his predictions are within the

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experimental limits of $|\dot{G}/G| < 4 \times 10^{-10}$/year [9]. Dicke's theory, which resulted from attempts to incorporate Mach's principle into gravitation, gives predictions of $\dot{G}/G$ within present experimental limits and, in addition, predicts spatial variations in G, as do several other metric theories of gravity [4]. Time variations in the fine structure constant α have been proposed by Gamow [10]. Fine structure measurements of distant galaxies and radioactive decay data from ancient rocks show that $|\dot{\alpha}/\alpha| < 10^{-15}$/year [6]. Spatial variations in α are ruled out by Eötvös experiments indirectly by Misner, Thorne, and Wheeler [11] since electromagnetic energy constitutes a sizable fraction (10^{-3}) of the rest energy of atoms. The strong interaction coupling constant g_0 is known to be spatially constant because of the null result of the Eötvös experiment by this same type of reasoning. Spatial variations in α and g_0 are ruled out directly by redshift experiments since electromagnetic and strong forces are involved in the hydrogen hyperfine transitions.

The situation with the weak interaction coupling constant β is somewhat different. From the decay of rhenium 187 to osmium 187, Dyson [6] has concluded that $|\dot{\beta}/\beta| \leq 10^{-10}$ year. This is done by comparing the present decay rates with ancient ones from molybdenite ores. This still allows a substantial variation in β over the age of the universe and does not rule out a time dependence of β of the form $\beta \sim t^{-f}$ where f is a small fractional exponent [12].

The fraction of rest mass energy contributed by the weak interactions is much smaller than that due to the strong or electromagnetic interactions. Early estimates [13] gave this fraction as 10^{-11} for the parity nonconserving part of the interaction, and a recent calculation by Haugan and Will [14] indicates that the parity conserving part of the interaction contributes a somewhat larger (10^{-8}) fraction to the rest mass. Present Eötvös experiments are conservatively rated as accurate to one part in 10^{11} [2, 3]. (Braginsky claims 1 part in 10^{12}, but there is some dispute about this). Therefore, in contrast to the strong and electromagnetic interactions, violations of the WEP by the weak interactions would only show up at a very low level in Eötvös experiments for the parity conserving part of the interaction and not at all for the parity nonconserving part of the interaction (which is responsible for beta decay). A major goal of space Eötvös experiments is to increase the accuracy to the point where weak interaction equivalence principle violations might show up.

The previously mentioned work by Misner, Thorne, and Wheeler [11] gives a means by which limits on variations in the fundamental interaction constants can be given to be consistent with Eötvös experiment. The argument requires that variations in β can be no larger than

$$\frac{\Delta \beta}{\beta} \sim \frac{e}{f} \frac{\Delta U}{2C^2} \tag{1}$$

where

ΔU = change in gravitational potential

C = speed of light

f = fractional difference in rest mass energy between gold and aluminum due to weak interactions

e = fractional accuracy of Eötvös experiment using gold and aluminum.

If we assume $e \sim f$, which is a fair assumption for the weak interactions but could be off by a few orders of magnitude, then $\Delta \beta / \beta \sim \Delta U / 2C^2$ so that Eötvös experiments put rather stringent limits on variations in β. This result is somewhat surprising in view of the small contribution to the rest mass energy due to the weak interaction.

The relating of possible variations in β to the accuracy of present Eötvös experiments is based on two assumptions which are on very solid foundations in nongravitational physics, namely, mass energy equivalence and energy conservation. However, when a gravitational field is present, modifications could

possibly occur. General Relativity requires local energy conservation (T^{ν}_{μ}; $\nu = 0$), but problems arise when one attempts to describe the energy content of a gravitational field since it can be eliminated at any point by an appropriate coordinate transformation. The previously mentioned local conservation law leads directly to geodesic motion and is thus one of the properties of metric theories of gravity we are trying to test. Theories designed to incorporate Mach's principle directly [15] have no global conservation laws whatsoever and only approximate local conservation laws under certain circumstances. Local conservation laws and Mach's principle may be difficult to reconcile in the end.

Finally, we point out that this argument refers only to variations in β, not in other factors in the expression for the beta decay rate; i.e.,

$$\Gamma \sim 2\pi |H_{if}|^2 \rho_f$$

where H_{if} is the matrix element of the Hamiltonian ($H_{if} \propto \beta$) and ρ_f is the density of final states. The problem is whether one can infer that H_{if} satisfies the equivalence principle if H_{00}, the contribution to the ground state energy, does; and this question is not addressed by the energy conservation arguments.

For all these reasons, it is believed that while the criterion given by equation (1) is a useful one, larger variations in β may occur. Finzi [16] suggests that a substantial variation in β (a factor of 1.3 to 2.0 at the surface of the Sun) can account for the anomalously low value of the solar neutrino flux. This type of variation would have important implications for astrophysics.

The question then arises: Why not measure β directly as a function of altitude or gravitational potential? This would uncover any spatial variations in β that would lead to anomalies in Eötvös experiments and would be a test of SEP as well.

Another alternative is to consider the beta decay process as a type of clock. Atomic clocks are based on atomic transitions which are governed by the electromagnetic interactions. Will [17] has shown that for nonmetric theories, the redshift depends on the type of transition on which the clock is based. He proposes[2] to fly different types of clocks in orbits which have large gravitational potential changes and compare the proper clock rates. Since a beta decay clock is based on an entirely different interaction, it would be an ideal candidate for such an experiment. The problem is that while one has definite predictions from nonmetric theories of SEP violations for electromagnetic clocks, it is not clear which violations one might expect for weak interaction clocks. The theory is not adequate to give definite predictions, although Nordvedt [18] has suggested a possible type of violation of SEP which might occur. Despite the uncertain predictions and because of the lack of experimental evidence previously mentioned, it is important to develop a precise beta decay clock to test SEP.

It is believed that the type of experiment described here is only one of a large number which could be suggested to test the Machian philosophy that the universe as a whole is related to and, in fact, determines the local physics and that in an evolving universe one should be able to measure spatial and temporal variations in the local physics. This type of experiment is also related to the relational theory of time [15] which implies that time is not an independent variable and that each interaction may define its own time scale.

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To further strengthen the case for this experiment, the following statements are cited from R. H. Dicke's 1961 Varenna lectures [19]:

"However, and this important point requires emphasis, none of these experiments says anything about the constancy of the weak interaction constant or the gravitational constant. These interactions contribute too little to the binding of a mechanical system to enter into the consideration based on self energy. We conclude therefore that clocks based on the two weak interactions may not keep time in accordance with the strong interaction clocks.

Finally, it must be stated that while there appears to be direct experimental support for the weak equivalence principle, the support for the strong principle is indirect and is limited to the constancy of the strong interactions. There seems to be little, if any, reason for considering the weak interaction constants to be constant. They could be functions of some field determined by the structure of the universe.

If one wishes to incorporate Mach's principle into relativity, there appears to be a conflict with the strong Equivalence Principle, for the strong Equivalence Principle demands the constancy of all physical constants, including G. However, as was noted above, the gravitational interaction is one of the two weak interactions, the constancy of which could not be supported by experimental evidence."

II. SCIENTIFIC GOAL

The scientific goal of the proposed experiment is to verify that the weak interaction coupling constant β is, in fact, a constant independent of position in a gravitational field, as required by the equivalence principle. This will be done by measuring the proper rates of beta decay at different points in a gravitational field with a precise electromagnetic clock as a reference. The accuracy goal of this experiment has not been decided upon as yet; but an accuracy of 1 part in 10^6 is clearly attainable without much difficulty, and higher accuracies may be possible with optimization of detector design and careful analysis of statistical properties of the data. The change in gravitational potential over which this constancy to at least 1 part in 10^6 will be verified will be the maximum available. The ideal case short of a solar orbit would be an elliptical Earth orbit with as low a perigee as possible. In this scheme a periodic modulation of the gravitational potential would occur, and one could look for only the periodic fluctuations in beta decay. This would provide a powerful tool for eliminating extraneous nonperiodic fluctuations of no interest to the experiment.

The importance of this experiment lies in the fact that it is one of the few direct verifications of SEP. Since the SEP is the basis for our belief in metric theories of gravity, it is important to have as many direct experimental tests of this principle as possible. It is by no means intuitively or logically obvious and requires experimental verification just as any statement concerning nature. The metric structure of gravity is the basis for our views concerning the structure of space-time and extends into microphysics as well as to the large-scale structure of the universe.

To illustrate how a violation of SEP could occur, consider how Mach's principle could suggest such a violation. If the inertia of matter arises from its mutual interaction with the matter in the rest of the universe, then it is reasonable to suspect that inertial mass could be a function of position. Thus, in a Machian theory rest mass would be expected to vary in the proximity of large masses. Such a variation is ruled out to considerable accuracy for the strong and electromagnetic contributions to the rest mass. However, as previously mentioned, this is not the case for the weak interaction contribution to the rest mass. Herein lies the motivation for this experiment and the suggestion that a positive result is perhaps not out of the question. We intend to investigate theories which predict these kinds of violations of SEP and determine the level at which one would expect these effects to occur.

The importance of a positive result to this experiment (i.e., a violation of SEP) is that it would change the whole structure of physics and compel theorists to look for a fundamental theory of gravity that is more Machian in its predictions. A negative result would give added confidence in the metric nature of space-time. While other tests of SEP may be proposed, β and G are the only fundamental constants in which one can expect substantial variations; therefore, this experiment will continue to be important in the future.

III. NEED FOR SPACE

This experiment requires a beta decay clock to be transported over as large a gravitational potential difference U as possible. A spatial dependence of β measured in the rest frame of the clock is being sought of the form

$$\beta = \beta_0 \left(1 + \alpha \frac{U}{c^2}\right)$$

where C is the velocity of light and α is an unknown parameter on which we propose to put upper limits. The experiment must be done in a time period commensurate with the half-life of the radioactive source in the experiment. Sources with long half-lives are available, but their specific activity is low and it may be difficult to achieve a high count rate. Also, problems with self-absorption with such sources may arise. The accuracy of the experiment depends on the count rate available as well as the change in the gravitational potential available (to be discussed later).

Considering these points, an experimental situation must be selected which will maximize the accuracy of the experiment, i.e., minimize the upper limit on α. There are several possible situations. The least accurate is an Earth-based experiment which uses the changing gravitational potential of the Sun due to the daily rotation of the Earth. This gives $\Delta U/C^2 \sim 8 \times 10^{-13}$. This experiment is planned as a first step to gain information on the accuracy of a laboratory clock and experience with the data analysis. The next step would be an orbital experiment. From the surface of the Earth to low Earth orbit, $\Delta U/C^2 \sim 5 \times 10^{-11}$. The experiment could be repeated several times to eliminate fluctuations which are not dependent on $\Delta U/C^2$. This could be improved upon with an elliptical orbit for which $\Delta U/C^2 \sim 6 \times 10^{-10}$. These latter two experiments could be done with time scales for which it would not be difficult to find a source with appropriate half-life. The orbital experiment is attractive because U is modulated periodically and nonperiodic effects could be filtered out of the clock data. On a longer time scale, an Earth-based experiment could be done using the eccentricity of the Earth's orbit to produce periodic variations in U on the order of $\Delta U/C^2 \sim 3 \times 10^{-10}$. This experiment would require many years to obtain full accuracy, and it is not clear at present whether suitable sources are available. The ultimate step would be a solar orbit where $\Delta U/C^2 \sim 10^{-7}$. Here one enters the realm in which the accuracy of measuring β (approximately 1 part in 10^5) approaches $\Delta U/C^2$, and the point is reached where positive results might be expected. The other experiments could be considered preludes or development efforts for this ultimate experiment.

IV. EXPERIMENT DESCRIPTION

The proposed experiment will consist of the following elements.

A. Radioactive Source

The use of a source based on the phenomena of electron capture rather than electron or positron emission is proposed because, for the latter case, the particles exit with a spectrum of energies extending to zero and a very stable discriminator would be required. For electron capture, however, one can measure the associated emission of X-rays and Auger electrons which have well-defined energies and can be counted very easily. It is usually assumed that the interaction responsible for electron capture is the same as for positron decay, but this has not been demonstrated. The sources being considered are:

Substance	Half-Life	X-ray Energy
Argon 37	34.3 days	2.6 keV
Iron 55	2.7 years	5.9 keV
Nickel 59	8×10^4 years	6.9 keV

Nickel 59 would be ideal for a long-duration experiment because of its long half-life. However, a sufficient count rate may be difficult to obtain, and self-absorption problems may be encountered. Argon 37 is the only reasonable gaseous source available. It has a short half-life but would still be suitable for an orbital mission. Iron 55 is readily available. Many other sources are available and will be studied. A source is needed which has a sufficiently high count rate that the limitation is in the detector, not the source. This does not appear to be a problem for most sources.

B. Detector

The question here is whether to use a gas or solid-state detector. Because the count rate needs to be maximized, the critical parameter is the ionization collection time of the detector. This appears to be lower in gas detectors, but further study is needed on this matter. Gas detectors would require Argon 37 with its low half-life. A possible detector scheme would be multiwire proportional counters with Argon 37 as the gas. A counter could be attached to each wire so the total count rate would be large. One hundred wires would give an order of magnitude increase in accuracy over one wire. There are many problems which need to be investigated for such a counter, such as the effect of impurities in the gas and the long-term effects of such a high count rate. If solid-state detectors are chosen, a source such as iron 55 could be deposited on or in the detector, thus resulting in a count rate of high stability. Whether the count rate for such a scheme is sufficient needs to be investigated.
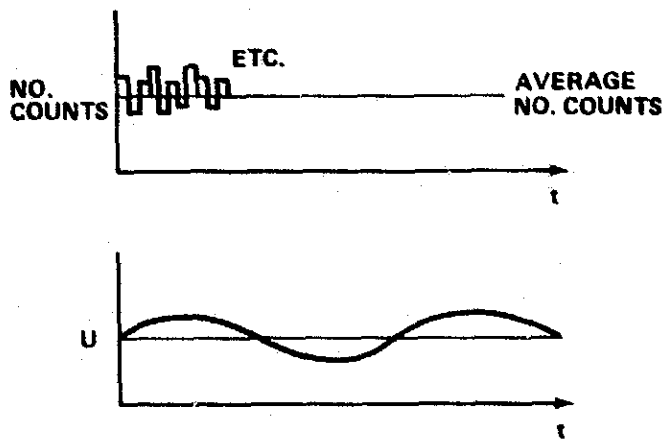
C. Counters

Electronic counters of high speed are needed to count the pulses from the detectors. These are available but need to be purchased for a laboratory demonstration. Amplifiers are also required as inputs to the counters. It will be necessary to cascade several counters for high count rates.

D. Electromagnetic Clock

The experiment requires an electromagnetic clock of sufficient precision to time the period over which the X-rays are counted. Such clocks are readily available. A cesium or rubidium clock would be of more than sufficient accuracy. The minimum acceptable degree of accuracy needs to be determined. The clock will be used to turn the counters on and off. The simplicity of this basic detector scheme illustrates that this experiment will be relatively inexpensive compared to other relativity experiments. This is one of the virtues of this type of experiment, but it is believed that fundamental knowledge can be gained if the accuracy is pushed to the limits.

V. EXPERIMENTAL PROCEDURES

The basic idea of this experiment is to modulate the gravitational potential in some preferably periodic fashion and look for corresponding changes in the rate of electron capture. Therefore, time intervals that are small compared with the modulation period will be selected, and the total number of electron captures will be counted in each of these time intervals. The length of the time intervals will be measured by an electromagnetic clock. The data in the experiment will be as follows:

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The output from the counters will be recorded on magnetic tape together with the time, and periodic fluctuations will be searched for in the electron capture rate. Therefore, the experimental procedure is simply recording the number of counts in specified time periods.

VI. BETA DECAY CLOCK PROGRESS FOR PAST TWO YEARS

1) A lower limit on the accuracy of a beta decay clock was actually demonstrated to be 5×10^{-5} by Peter Parker.[3]

2) Proportional counters with an Fe^{55} source appear to give the highest count rate.

3) The significant error sources in this type of experiment are:

a) Discriminator stability

b) Dead time stability

c) Detector efficiency stability (e.g., due to pressure variations in gas detectors)

d) Statistical limitations ($\propto \sqrt{N}$). It is not clear which is the dominent source of error at this time.

4) Several orders of magnitude improvement should be possible by using a synchronous detection scheme (i.e., elliptical orbit). This will reduce the random fluctuations in the error sources listed in item 3) by $1/\sqrt{n}$ where n is the number of orbits. n could be $\sim 10^4$ in Earth orbit. It will eliminate systematic fluctuations in error sources that are not at orbit frequency. The extent to which this will reduce the effect of overall systematic errors listed in item 3) is not known and depends on the power spectrum of these types of fluctuations.

5) Drifts in the error sources listed in item 3) need not be eliminated. If they can be measured and the associated count rate drifts can be accounted for, that is all that is necessary. That is, drifts in count rate can be corrected for, and the accuracy is determined by the stability after all possible corrections are made. For example, discriminator drifts can be measured directly

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and used to eliminate associated count rate fluctuations in the data. The extent to which this can be done requires construction of an actual working model of the experiment.

6) The limitations on proportional counter count rates are 10^7 to 10^8 counts/sec for one detector. For a 10-year mission this is $3 \times 10^{15} \sim 3 \times 10^{16}$ counts for one detector.

7) Source activity limitations are not a problem for Fe^{55}. One can easily get 10^{10} counts/sec.

8) Multiple detectors can increase the count rate and thus lower statistical fluctuations. It is possible to construct a multiwire proportional counter with 10^3 wires, and this is actually done in cosmic ray experiments.

9) For 10^3 detectors at 10^7 to 10^8 counts/sec, 3×10^{18} to 3×10^{19} counts are obtained for a 10-year mission. This gives approximately 1 part in 10^9 accuracy due to statistical fluctuations. This approaches the $\Delta U/C^2$ level for Earth orbit and exceeds that level for a solar orbit.

In conclusion, a low accuracy test for variations in beta decay rates due to gravitational potential is believed to be currently possible. A test at the 10^{-5} to 10^{-6} level in Earth orbit could be done with existing technology. Accuracy levels approaching the $\Delta U/C^2$ level would probably require a solar orbit and substantial detector development.

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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