The Theoretical Significance of Experimental Relativity

UNIVERSITÀ DI PISA
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The Theoretical Significance of Experimental Relativity

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EDITOR'S PREFACE

Seventy years ago when the fraternity of physicists was smaller than the audience at a weekly physics colloquium in a major university, a J. Willard Gibbs could, after ten years of thought, summarize his ideas on a subject in a few monumental papers or in a classic treatise. His competition did not intimidate him into a muddled correspondence with his favorite editor nor did it occur to his colleagues that their own progress was retarded by his leisurely publication schedule.

Today the dramatic phase of a new branch of physics spans less than a decade and subsides before the definitive treatise is published. Moreover, modern physics is an extremely interconnected discipline and the busy practitioner of one of its branches must be kept aware of breakthroughs in other areas. An expository literature which is clear and timely is needed to relieve him of the burden of wading through tentative and hastily written papers scattered in many journals.

To this end we have undertaken the editing of a new series, entitled *Documents on Modern Physics,* which will make available selected reviews, lecture notes, conference proceedings, and important collections of papers in branches of physics of special current interest. Complete coverage of a field will not be a primary aim. Rather, we will emphasize readability, speed of publication, and importance to students and research workers. The books will appear in low-cost paper-covered editions, as well as in cloth covers. The scope will be broad, the style informal.

From time to time, older branches of physics come alive again, and forgotten writings acquire relevance to recent developments. We expect to make a number of such works available by including them in this series along with new works.

Elliott W. Montroll
George H. Vineyard

PREFACE

This thin volume represents the notes, including a number of reprinted articles, for my course of lectures at the Les Houches summer school in July, 1963. The lectures were devoted to a discussion of a few key experiments and to their interpretation. Where so few experimental facts are available, one is driven to extract the maximum in theoretical interpretation, and these notes represent my attempt to both define and observationally delimit a class of relativistic theories of gravitation.

I consider it a privilege to have been able to spend two weeks in conversation and seminars with some of the best young theorists from both sides of the iron curtain, and as an experimentalist I attempted to counteract in some small measure the decided tendency in times past for General Relativity to develop into a formal science divorced from both observations and the rest of physics. A well known physicist once remarked to me that Einstein's General Relativity was such a beautiful theory that it was a shame that there were so few experiments. An examination of the scientific literature of the past 50 years will testify to the truth of this statement, the number of experimental papers being entirely negligible in comparison with the flood of theoretical publications, mostly formal.

Because of the great weakness of gravitation, results are far easier to obtain by calculation than by measurement. The experimentalist is unable to complement and guide the theorist in the manner that occurs in the other parts of physics. This elementary difficulty is a fact that the experimentalist must face, but the very lack of relativity experiments sharpens the challenge and increases the importance of the few experiments that are possible.

In my view, the grand opportunity for the experimentalist lies not in the applications of General Relativity but rather in its foundations. It would be a shame for dozens of very able theorists to devote a second half century to developing the results of General Relativity only to discover eventually that the theory is defective, that some basic assumption is incorrect.

In attempting to establish an observational basis for a relativistic theory of gravitation, I drew from the most important observations available in July 1963, including several new ones. However, the facts were so few that I was unwilling to pose the usual simple question, to ask if these few observations were compatible with General Relativity. I was curious to know how many other reasonable theories would also be supported by these same facts.

The observational results considered can be classified as follows:

a) Null experiments of extreme precision.
b) Null experiments of ordinary precision.
c) The famous three tests of General Relativity.
d) Cosmological observations.

Although all four types of experiments were covered in my lectures, in the two short weeks available I could not develop in my notes parts (c) and (d) to the extent that I would have liked. This is made up in part by several of the reprinted articles in the appendices.

In broadening the class of acceptable theories, I was unwilling to consider any but relativistic field theories. I considered it important to require general covariance and to permit only field theories derivable from an invariant action principle. The resulting very large class of theories, which includes General Relativity as special case, is explored in Appendix 4.

The reason for limiting the class of theories in this way is to be found in matters of philosophy, not in the observations. Foremost among these considerations was the philosophy of Bishop G. Berkeley and E. Mach.

It proved to be impossible to broaden the class of gravitational theories in this way without questioning two of the cardinal principles of General Relativity, the strong equivalence principle and the principle of a purely geometrical description of gravitation.

The strong equivalence principle is so sweeping in its implications that it reduces this large class of theories to a single example, that of Einstein. The situation regarding the geometrical interpretation is a bit more complicated. In the case of Einstein's theory, many definitions of a Riemannian geometry are possible but only one falls out in a natural way. If this definition is used, the gravitational field is described in purely geometrical terms, the field tensor being intrepreted as the metric tensor of the geometry. However, for every other theory in this very large class, the introduction of an operationally defined metric tensor is either impossible or else ambiguous, a large number of equally satisfactory definitions being possible.

Under these conditions it proved to be necessary to demote geometry from the central position that it occupies in Einstein's theory to a secondary position. Einstein's theory is not functionally damaged by this reinterpretation, although many would regard such a field theoretic interpretation as less elegant and beautiful than the geometrical one. There is probably room for disagreement on such questions of aesthetics; in any case their importance for physics can be questioned.

It is interesting to note that although this class of possible relativistic field theories of gravitation is enormous, the experiments discussed in the notes make unlikely any but a very limited sub-class, containing only Einstein's theory and the various theories requiring both tensor and scalar zero mass fields. This interpretation of the observations is discussed in the main body of the notes as well as in Appendix 4.

Owing to the short period in which they were written, the notes are uneven, certain sections receiving an adequate treatment but other equally important parts being almost completely ignored. Perhaps the most serious lack is a discussion of Mach's principle, for the philosophy of Berkeley and Mach always lurked in the background and influenced all of my thoughts.

During our two week stay at Les Houches Mach's principle was frequently under discussion. Upon our arrival at Les Houches on a Sunday evening, my daughter, Nancy, and I were welcomed by Bryce DeWitt with the invitation to

join a Mach's Principle Seminar scheduled to start in a few minutes. This was the second of a series of some half dozen exciting and at times contentious seminars on the subject. Above all else, these seminars conducted by F. Karolyhazy, F. Gürsey, J. A. Wheeler and me showed that there was no general agreement on the meaning, significance or importance of this principle for physics. However, my own thinking in recent years has been strongly conditioned by this philosophy.

As mentioned above, the philosophy of Berkeley and Mach furnished the philosophical framework for the class of theories described in Appendix 4. The physical picture is one of a 4-dimensional world populated by structureless particles. These particles are not only the real and virtual particles of laboratory physics, but also the zero mass bosons, mostly virtual, assumed to be responsible for gravitational and inertial forces. Contrary to the philosophy of Newton but consistent with Mach's viewpoint, inertial forces are pictured in Appendix 4 as "real" being acceleration dependent forces having their origin in collisions with gravitons, particles associated with a symmetric tensor field.

As of this writing we seem to be very far from a situation requiring gravitons and the quantization of the gravitational field, therefore it is helpful to remember that boson fields do not exhibit important quantum fluctuation effects when they are strong and contain only low frequency components. While in our speculations we may have pictured a space populated with a host of gravitons, it seemed reasonable to develop a theory of *classical* boson fields interacting with *classical* particles. It seemed certain that almost all the interesting gravitational physics could be encompassed in such a non-quantized treatment of the gravitational field or fields. The gravitational interaction is viewed as basically not different from other interactions, and that the treatment as a classical unquantized field should be regarded as a good approximation to a proper quantized treatment.

The empty physical space I picture as a void without properties, the physical properties of the space, when populated, arising wholely from its material content. As emphasized by Bishop Berkeley, the motion of a single test particle in such an otherwise empty space is a meaningless physical concept; but populate this space with particles and the motion can be given meaning through the altered pattern of collisions with the particles filling the space, a geometrical point being identified with a space-time coincidence of two particles. Alternatively, when quantum fluctuations are beyond our vision, a set of invariants derived from the various massless boson fields might be used to help identify a geometrical point.

Mach's ideas about the nature of inertial forces were the anti-thesis of the philosophy of Newton and Locke. From our first contact with physics we have been exposed to Newton's philosophy. We all learned that forces were the pushes or pulls which one body exerted upon another, and that the forces acting upon a body were to be summed, divided by the mass of the particle, and equated to the acceleration of the body. The acceleration was to be pictured as *caused* by this force. When we studied Einstein's relativity, both Special and General, we again encountered this essentially Newtonian idea but expressed in a four dimensional form.

As pointed out already in 1710 by Bishop Berkeley, and later elaborated by E. Mach, the Newtonian scheme has logical difficulties. The acceleration is to be reckoned with respect to "absolute space", a concept emphasized by Berkeley to be without an observational basis. What one actually measures is always an acceleration relative to other, generally distant matter in the universe.

As emphasized by Mach, with this interpretation of the acceleration there is no longer a clear distinction between the "real" (eg. electrical and nuclear) forces and "illusionary" (inertial) forces of physics. While Mach's writings are difficult to interpret, it appears to have been his view that inertial forces were action-at-a-distance acceleration dependent forces produced by interactions with the distant matter of the universe. He interpreted such inertial forces as just as real as other action-at-a-distance forces such as electromagnetism or gravitation.

To give a modern interpretation to Mach's ideas it is necessary to interpret inertial forces as acceleration dependent interactions of a particle with a field generated by the distant matter in the universe. Using the standard machinery of Lorentz invariant field theory, it is easy to show the forces generated by a symmetric tensor field interacting with a particle are of two types, being velocity and acceleration dependent. However, as shown by W. Thirring, the introduction of such a tensor field destroys the observability and physical significance of the Minkowski metric tensor of special relativity. The interaction of a tensor field with matter so distorts meter sticks and clocks that they no longer measure the Euclidean geometry of special relativity.

In Appendix 4 the Newtonian philosophy is abandoned; relativistic field theory is developed without the introduction of either a metric or affine connection. The arbitrarily chosen coordinate system is to be interpreted only as a convenient labeling of an almost continuous pattern of collisions between the particles filling the space. The physical concepts of distance, curvature, or geodesic path are to be avoided until the dynamical problems are solved. After the equations of motion are obtained, for certain combinations of zero-mass boson fields it is useful to introduce a definition of the metric of a Riemannian geometry. For other combinations, a physically meaningful definition is impossible.

Palmer Physical Laboratory
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February 4, 1964

CONTENTS

Introduction

Before discussing in detail the present status of experimental work on gravitation, it is necessary to consider briefly the unique problems and opportunities faced by the experimentalist working in this field. Experiments seems to play quite different roles, and to present very different problems, in the various fields of physics. For example, in high energy physics the experimenter is the explorer, new particles are still being discovered, and even the qualitative aspects of their interactions are not yet completely understood. In this field there is not yet a satisfactory theory and the experiments are essential for the construction of a theory.

On the other hand, in solid state physics the basic physical laws are well known, for the electromagnetic interaction of electrons and nuclei with each other is well understood in its broader aspects. It is only the complications of the many body problem that prohibits a complete theoretical treatment of solid state physics. Experiments in this branch of physics provide insight into the complications of the many body problem.

The problems of the experimentalist working on gravitation differ from both of the above. Here there is an elegant, well defined theory but almost no experiments. The situation is almost orthogonal to that in both high energy physics and solid state physics. Far from experimental science being a crutch on which the theory leans, in the case of general relativity, theory has far outstripped experiment, and the big problem is one of finding significant experiments to perform. This situation raises serious problems for theory and our understanding of gravitation. For where there are no experiments the theory easily degenerates into purely formal mathematics.

At this stage it might be asked whether either experiment or theory in this field is important to the rest of physics. Certainly it was the prevailing attitude during the thirties and forties that general relativity was of little importance to a physicist. This was caused by an apparent lack of connection with laboratory science. In fact, a slightly naïve application of the equivalence principle seems at first glance to force this point of view. If gravitation is transformed away locally (i.e., a coordinate frame, locally inertial, is chosen), then externally produced gravitational effects apparently disappear in the laboratory. From this it is a short step to conclude that the external universe is without effect on the laboratory and that cosmology is of no concern to the physicist.

But certainly this is too provincial a point of view. The physicist cannot limit his horizon to the narrow confines of his little laboratory. Whether he likes it or not he is in the universe. His apparatus is made of cosmological stuff, and he should be curious about its origins. The walls of his laboratory are penetrated by neutrinos, probably by gravitons, and possibly by scalarons generated by the distant matter in the universe in ancient times. Also, the structure of the elementary particles, his stock and trade, may be dominated at small distances by gravitational effects.

In other fields of physics the experimentalist is faced with the problem of choosing the most important out of a large number of possible experiments. With gravitation the problem is different. There are so few possible experiments, and their importance is such, that any and all significant experiments should be performed. As an example, it can be argued that the gravitational red shift is a result to be expected from little more than energy considerations (see later discussion) and is not a significant test of general relativity. While to some extent this is true, I feel that an experiment such as this is worth while, as it adds to the general body of knowledge and reduces the area of conjecture.

While all relativity experiments are important, in my view the most important are the highly precise null experiments to be discussed. These, carefully interpreted, provide a substantial observational foundation for certain parts of the structure of general relativity and also show where information is lacking. Second most important are the so-called fundamental tests of general relativity, such as the relativistic perihelion rotation of planetary orbits. While these do not have the precision that one would like, they provide valuable insight into the form of the field, or fields, associated with the central force problem. The third part, which could be easily rocketed into first place of importance by a significant discovery, is the general area of cosmological effects. These concern a wide variety of subjects: possible gravitational or scalar waves from space, the effects of a quasi-static scalar field generated by distant matter (if such a field exists), the continuous creation cosmology (which should be either laid to rest or else cured of its ills), Schwarzschild stars if they exist (a Schwarzschild star is one for which the star's matter is falling down the gullet of the Schwarzschild solution), massive generators of gravitational radiation, the global aspects of the structure of the universe, and the origin of matter. All these and many more are subjects concerning effects on a cosmological scale. These effects, if they could be observed, would give information about the most fundamental of the problems of physics.

It is worth asking why experimental work on gravitation is so different and has such a different status from experiments in other fields. This is probably due to the extreme weakness of the gravitational interaction, only 10^{-40} of the strength of the strong interactions. Because of this great weakness, an experimentalist is forced to modify his conceptions of what an experimentalist is and does. Traditionally an experimental physicist has been able to isolate a problem in the laboratory and to devise controlled experiments designed to look at one aspect of his complex problem. He has made real progress by concetrating on one specific thing. However, because of the great weakness of gravitation, the experimentalist working on gravitation might like to perform experiments on an astronomical scale. For example, he might like to take two bodies of 10^{33} gm mass and a density of 10^{6} gm per cubic centimeter and whirl them about each other at high speed. He clearly cannot do this in the laboratory, but he may find nature performing just such an experiment for him if he looks hard enough.

Experiment and observation can become intertwined in this field of physics, and will probably become more so in the future. The chief difference between the experimental physicist trying to get information from observations on the galaxy and the astrophysicist doing the same, is that the physicist, working on a particular gravitational problem, is considering the astrophysical observations for a specific physical reason. He is not concerned with galactic structure *per se* but views the whole galaxy as a giant laboratory in which many millions of experiments are being carried out simultaneously on an enormous scale. The physicist may want to look around carefully among this enormous number of colossal "experiments" to see if by some fluke one of them is just the one that he would have liked to perform in the laboratory himself. While his chance of finding exactly the experimental setup that he would have liked is rather small, there may be many of these "experiments" that have some bearing on his particular problem.

In the cosmological field, the ground under foot, the interior of the earth, element abundances, and the form of the solar system are all capable of providing important clues to the answer of important physical questions. Here there is no paucity of relativity experiments to perform; rather the problem is one of interpretation. Almost invariably the astrophysical and geophysical systems are so complex that a simple, clear, and unambiguous answer to a straightforward physical question cannot be obtained. However, a limited answer has some validity, for it can contribute slightly to a gradually evolving picture of the physical situation. Each fact by itself may have only a very small importance, but taken all together these facts can constitute an important part of our total knowledge.

I. Null Experiments

Eötvös Experiment

Of the various null experiments, perhaps the most important is the Eötvös experiment, first performed in 1889 by Baron Roland v. Eötvös and recently repeated by the author's research group. This experiment showed with great precision that all bodies fall with the same acceleration. Actually the roots of this experiment go back much farther than this. Newton, and many others after him, demonstrated experimentally that the gravitational acceleration of a body was independent of its composition. Even the ancient Greeks must have had some ideas along this line, and it seems likely that the famous theoretical proof of Aristotle that the gravitational acceleration of a heavy body was very much greater than that of a light body must have flown in the face of the everyday observations of the Greek world. It seems likely that, long before the Greeks, primitive man must have observed that a lizard knocked out of a tree by a stone fell to the ground almost simultaneously with the stone.

The importance of the Eötvös experiment rests primarily upon the fact that the null result of this experiment is a *necessary* condition to be satisfied if Einstein's general relativity is to be valid. The geodesic motion of a structureless and spinless particle is a result of general relativity. The unique character of the trajectory is an elementary result which can even be derived directly from the equivalence principle. For small laboratory sized objects, accelerated in the gravitational field of the sun or earth, the effect of finite size or of spin angular momentum on the trajectory is negligible, and to a good approximation geodesic motion would be expected.

In the experiment performed by the Princeton group, the gravitational acceleration toward the sun of small gold and aluminum weights were compared and found to be equal with an accuracy of about a part in 10^{11}. Hence, the *necessary* condition to be satisfied seems to be rather satisfactorily met. Perhaps a more interesting question is this: To what extent is this experiment also a *sufficient* condition to be satisfied in order that general relativity be valid?

Before discussing this, it is important to note that gold and aluminum differ from each other rather greatly in several important ways. First, the neutron to proton ratio is quite different in the two elements, varying from 1·08 in aluminum to 1·5 in gold. Second, the electrons in aluminum move with non-relativistic velocities, but in gold the *k*-shell electrons have a 15 per cent increase in their mass as a result of their relativistic velocities. Third, the electromagnetic negative contribution to the binding energy of the nucleus varies as Z^2 and represents $\frac{1}{2}$ per cent of the total mass of a gold atom, whereas it is negligible in aluminum. In similar fashion, the virtual pair field around the gold nucleus would be expected to represent a far bigger contribution to the total energy than in the case of aluminum. Also the virtual pion field, and other virtual fields, would be expected to be different in the two atoms. We would conclude that in most physical aspects gold and aluminum differ substantially from each other and that the equality of their accelerations represents a very important condition to be satisfied by any theory of gravitation.

It should be remarked that no experiment can provide a *sufficient* condition for a theory to be valid, as all experiments have only a finite accuracy. But the accuracy of the Eötvös experiment is very great. Does this imply that the equivalence principle is very nearly valid? It will be shown that this is only true in a limited sense. Certain aspects of the equivalence principle are not supported in the slightest by the Eötvös experiment.

In order to understand the limited conclusions to be drawn from the Eötvös experiment, we must first consider the significance of the equivalence principle for relativity. In this connection it may be convenient to make a distinction between the strong equivalence principle upon which Einstein's general relativity is based and the weak equivalence principle supported by the Eötvös experiment. The strong equivalence principle might be defined as the assumption that in a freely falling, non-rotating, laboratory the local laws of physics take on some standard form, including a standard numerical content, independent of the position of the laboratory in space and time. It is of course implicit in this statement that the effects of gradients in the gravitational field strength are negligibly small, i.e., tidal interaction effects are negligible. The weak principle of equivalence says considerably less; it states only that the local gravitational acceleration is substantially independent of the composition and structure of the matter being accelerated.

The significance of the strong form of the principle of equivalence for relativity appears to be the following: This principle requires that the laws of physics, expressed in a coordinate system, locally inertial, shall take on some standard form and have some standard numerical content. As a laboratory, neither rotating nor accelerating, in gravity free space provides a particular example of the situation described above. the assumption that physical laws are correctly described in gravity free space by the usual Lorentz-invariant formalism implies that for the more general situation, where gravitation is present, the formalism should reduce locally to this standard Lorentz invariant form (with local Minkowski coordinate conditions).

It is well known that this interpretation of the equivalence principle, plus the assumption of general covariance is most of what is needed to generate Einstein's general relativity.

The numerical content of the locally observed laws of physics is contained in the dimensionless physical constants appearing in the formulation of physical laws. These include the ratios of the masses of elementary particles, the various coupling constants of the theory, such as the fine structure constant, and the ratios of the masses of elementary particles to the characteristic fundamental gravitational mass $(\hbar c/G)^{1/2}$. Thus, one of the assumptions of the strong equivalence principle is that these dimensionless "constants" are truly constant, i.e., coordinate independent.

It is evident that the weak principle of equivalence is supported directly and strongly by the Eötvös experiment. But does it also support the strong principle? As will be shown, the answer is a limited yes. An argument, due originally to Wapstra and Nijgh[1], and only a slight elaboration of a familiar derivation of the gravitational red shift formula, can be used to sustain in part the strong principle.

Before discussing the argument we shall consider briefly this derivation of the gravitational red shift. The red shift can be obtained from the null result of the Eötvös experiment, mass energy equivalence, and the conservation of energy in a static gravitational field and static coordinate system. With the assumption that the inertial mass of a body is given by its total energy, the Eötvös experiment shows with considerable accuracy that the passive gravitational mass, or weight, is proportional to the inertial mass, hence to the energy of the body. Now consider an atom with two internal energy states and consider an energy reservoir, both to be placed initially on the floor of the laboratory. Let the atom, originally in the ground state, be excited by withdrawing energy from the reservoir. Then let it be lifted to the ceiling in its excited state. Let a photon be emitted and the atom lowered in its ground state to its original position on the floor. If the photon is caught in the energy reservoir and all the energy, positive and negative, used in lifting and lowering the atom be then gathered up in the reservoir, the assumption that this total energy is conserved is sufficient to give the correct result for the red shift. The proof is elementary. Assuming mass-energy equivalence and the null result of the Eötvös experiment, the weight of a body is equal to its internal energy multiplied by the local gravitational acceleration g. The total work required to lift it an infinitesimal distance dx in the excited state and lower it in its ground state is

$$dw = gEdx \tag{1}$$

where E is the excitation energy. For energy conservation to hold, the energy of the photon trapped in the energy reservoir must exceed the original photon energy withdrawn by

$$dE = gEdx. \tag{2}$$

It should be noted that except for the null result of the Eötvös experiment this result depends only upon the assumptions of mass-energy equivalence and energy conservation. For this reason the gravitational red shift experiment is not a very strong test of general relativity. We shall return to this point later when the so-called three fundamental tests of general relativity are discussed.

Now let us consider the implication of the Eötvös experiment for the constancy of the dimensionless physical constants, hence for the strong equivalence principle. This is best discussed with an example. Consider the question of whether the fine structure "constant" is really constant, hence independent of position. If we again make the assumptions of energy conservation and mass energy equivalence, the above argument can be used to show that the fine structure constant could not vary appreciably with position.

In order to show this, let us first assume the contrary. Then the internal energy of the atom is a function of position, this for a variety of reasons. For example, the electrostatic self energy of the nucleus is proportional to $z(z-1)\alpha$. Also the electronic contribution to the total energy of an atom is approximately proportional to the square of the fine structure constant.

Once again assume a closed cycle in which the atom is first slowly lifted, this time in its ground state. In the raised position the atom is taken apart, being broken down either into elementary particles or into two or more atoms of smaller mass. These fragments are then gently lowered to the ground floor and reassembled into the original atom. Now it is easily seen that if the internal energy of the primary atom is a function of height, but not that of the fragments, the atom has an additional (anomalous) weight equal to the negative gradient of its internal energy. This is a necessary requirement for energy conservation. More generally, if the energies of the fragments are also variable, but by different amounts, the anomalous forces will be different for the fragments. It should be emphasized that only energy conservation is required to exhibit these anomalous forces.

Now with the additional assumption that the inertial masses of the atoms and elementary particles are equal to their internal energies, anomalous gravitational accelerations must appear, contrary to the null result of the Eötvös experiment. The expected anomalous acceleration is equal to

$$\delta a = -\frac{1}{m}\nabla m \quad (c = 1) \tag{3}$$

The strongest test of the constancy of the fine structure "constant" is provided not by the electronic contribution to the energy of the atom, but by the electrostatic contribution to the binding energy of the nucleus.* Here the equality of the gravitational acceleration toward the sun of aluminum and gold, to an accuracy of a part in 10^{11}, implies that the fine structure constant could vary with position relative to the sun by only an extremely minute amount. The fractional gradient of the fine structure constant due to the presence of the sun, could not exceed 5×10^{-31}/centimeter, or else the gravitational acceleration of gold relative to the sun would differ by more than a part in 10^{11} from that of aluminum. This is a very severe limit to the constancy of the fine structure constant, for one might expect that if there were a

* We do not consider separately the effect of electromagnetic contributions to the self energy of the elementary particles.

cosmological effect leading to a variation of the fine structure constant, the effect of the sun's presence would be of the order of [2,3]

$$\delta\alpha \sim -\alpha^2 \frac{GM}{rc^2} \tag{4}$$

where $\delta\alpha$ is the change in the fine structure constant due to the presence of the sun, and M and r are the mass of and distance to the sun. If there were a variation in the fine structure constant as large as that given by equation (4), there would be an anomalous gravitational acceleration 5×10^6 times as large as the limit set by the Eötvös experiment.

It must be emphasized that this conclusion depends on the assumption of the equivalence of inertial mass and energy, and the assumption of energy conservation. The close connection between time displacement invariance and energy conservation would appear to require the energy conservation principle for a static gravitational field described in a static coordinate system. However, the assumption of mass-energy equivalence is not quite so compelling. As will be discussed more in detail in the next section, the interaction of a particle with a second massless tensor field would generally lead to an anomaly in its inertial mass. However, the second null experiment to be described makes the existence of more than one long range tensor field unlikely. Consequently, the equivalence of the inertial mass of a body and its energy is assumed here. It is believed, therefore, that Wapstra's argument for the constancy of physical "constants" is valid. However, to avoid any misconceptions it should be remarked here that this constitutes a compelling argument for the constancy of only some of the physical constants. Before discussing this point in some detail we first consider a closely related problem.

In recent years it has frequently been suggested that the gravitational pull on an antiparticle might be negative. This suggestion ignores the fact that this is incompatible with the requirements of general relativity. (Consider, for example, the implications for the laws of gravitation of energy confined to a small perfectly reflecting box, being converted back and forth from a pair state to a photon state. If the positron coupling were negative, the gravitational field generated by the box would decrease while in the pair state.)

Schiff[4] has shown that an argument based on the Eötvös experiment and the standard Lorentz invariant laws governing laboratory physics can be used to exclude this possibility. The argument is simple. In the virtual photon field of the nucleus there exists also a virtual pair field derived from the photon field. If the positrons in this pair field were to tend to fall, up not down, there would be an anomalous weight of the atom, substantially greater for large atomic number than small. It is concluded because of the null result of the Eötvös experiment that positrons and other antiparticles fall down, not up.

What then can be concluded from the Eötvös experiment about the constancy of the physical "constants"? The conclusion seems to be that all the dimensionless physical constants differing no more than a few powers of 10 from unity are constant or are very nearly constant.

There are two physical constants, differing from unity by many powers of 10, for which this argument is without validity. These are the fantastically small Fermi and gravitational coupling constants. They have values respectively of approximately 10^{-13} for the Fermi constant and 10^{-40} for the gravitational coupling constant. The gravitational and Fermi interactions are so weak that the resulting contribution to the self energies of the atom are negligible; consequently they have no important effects upon the gravitational acceleration and the Eötvös experiment. An alternative way of expressing the possible variation of a gravitational coupling constant is to remark that the gravitational mass $(\hbar c/G)^{1/2} = 2{\cdot}2 \times 10^{-5}$ gm may vary with respect to the masses of the elementary particles, or completely equivalently that the elementary particle masses may vary when compared with the gravitational mass. As will be discussed later the elementary particle masses would be expected to vary if these particles coupled with some long range, i.e., zero mass, scalar field.

If it some day should be shown that elementary particle masses were dependent upon such a field, this would be of considerable significance, for a scalar field, generated by the whole universe, would carry into the laboratory an effect dependent upon the structure of the whole universe. A physicist could hardly ignore cosmology if β decay rates and gravitational interaction strengths were to be dependent upon the dimension of the universe.

The above discussion has served to highlight the significance of the Eötvös experiment for relativity. Not only is the weak principle of equivalence supported directly and strongly by this experiment, but except for the question of the invariance of the gravitational and Fermi interaction strengths, the strong principle is also.

The Princeton Experiment. The early experimental work on the composition independence of the gravitational acceleration used pendulums. It was determined that, with considerable accuracy, the period of a pendulum was independent of the composition of the pendulum bob. This approach to the problem, using a pendulum, is apparently limited by the accuracy with which the period of the pendulum can be measured and also by the various effects disturbing the oscillation of the pendulum. Eötvös experiment differed in one important way from the earlier ones. His was a null experiment, i.e., he employed a static torsion balance, balancing a component of the earth's gravitational pull on a weight against the centrifugal force field of the earth acting on the weight. (While a centrifugal force field is an anathema to a teacher of elementary physics, in relativity it may be considered as an honest force, merely an aspect of the overall gravitational force field.)

In his torsion balance experiment, Eötvös employed a horizontal torsion beam, 40 cm long, suspended by a fine wire. From the ends of the torsion beam were suspended, one lower than the other, two masses of different composition. A lack of strict proportionality between the inertial and gravitational masses of the two bodies would lead to a torque tending to rotate the balance. In Eötvös apparatus there seems to be no good reason for the one mass being suspended lower than the other.

This experiment, first published in 1890 and later repeated, being published in 1922,[5] showed with an accuracy of a few parts in 10^9 that inertial and gravitational masses were equivalent. This was quite an achievement considering the time at which the experiment was done, and the techniques available at that time. With our more modern techniques we were only able to improve his results by $2\frac{1}{2}$ orders of magnitude.

The Princeton experiment, performed by P. G. Roll, R. Krotkov, and R. H. Dicke, was designed with the following points in mind:

(a) We wanted to use the acceleration toward the sun, rather than the centripetal acceleration due to earth's rotation, as the source of the inertial field. While the acceleration toward the sun is somewhat smaller, this deficiency is more than compensated for by the advantages of a controlled experiment. A great difficulty with using the earth's rotation as the source of the inertial force field is that it cannot be turned off. However, to explain the matter in egocentric terms, the sun moves around the earth every 24 hours, and any gravitational-inertial anomalies should appear with a 24-hour period rather than statically as in the case of the earth's centrifugal force field.

(b) Because of its large quadrupole moment, Eötvös' balance was quite sensitive to gradients in the gravitational field produced by nearby massive bodies, such as Baron Eötvös himself. To reduce difficulties of this type we used a three-fold symmetry axis in the torsion balance. This employed one gold weight and two aluminum weights at the three corners of a horizontal equilateral triangle. The dimensions of the triangle were kept small, only 6 centimeters on the side. Also the rotation of the torsion balance was observed remotely to eliminate gravitational disturbances produced by the observer.

(c) To eliminate disturbances produced by convective currents in the air a good vacuum was employed in the chamber containing the torsion balance. Also to reduce the air pressure gradient effects produced by thermal gradients in the apparatus, a good vacuum (10^{-8} mm) was used, and precautions were taken to hold temperature variations and gradients to very small values. The very low gas pressure also incidently greatly reduced the pressure fluctuation disturbances of the pendulum (i.e., Brownian motion effects), but this Brownian motion disturbance was usually unimportant when compared with the other disturbances, chiefly seismic in origin.

(d) As a means of controlling the temperature fluctuation and gradients, and of reducing ground disturbances, the instrument was located in a specially built remote instrument well 12 feet deep. This well was capped by a thermal insulating plug 4 feet thick. The instrument was operated remotely for months at a time without opening the well.

(e) To substantially eliminate the disturbances associated with the gradual creep of the suspension wire, it was replaced by a fused quartz fibre, coated with a thin film of aluminum.

(f) To eliminate the highly undesirable dynamical characteristics of an underdamped torsion balance, the rotation of the balance was sensed remotely and the resulting error signal fed back through a corrector network as a torque on the balance. This served not only to dampen the balance but to decrease its period.

(g) The balance was designed and built to eliminate magnetic contamination, as the fluctuations in the earth's magnetic field could otherwise lead to inordinately large disturbances of the balance.

(h) Insulating surfaces which could have become electrostatically charged were eliminated from the balance.

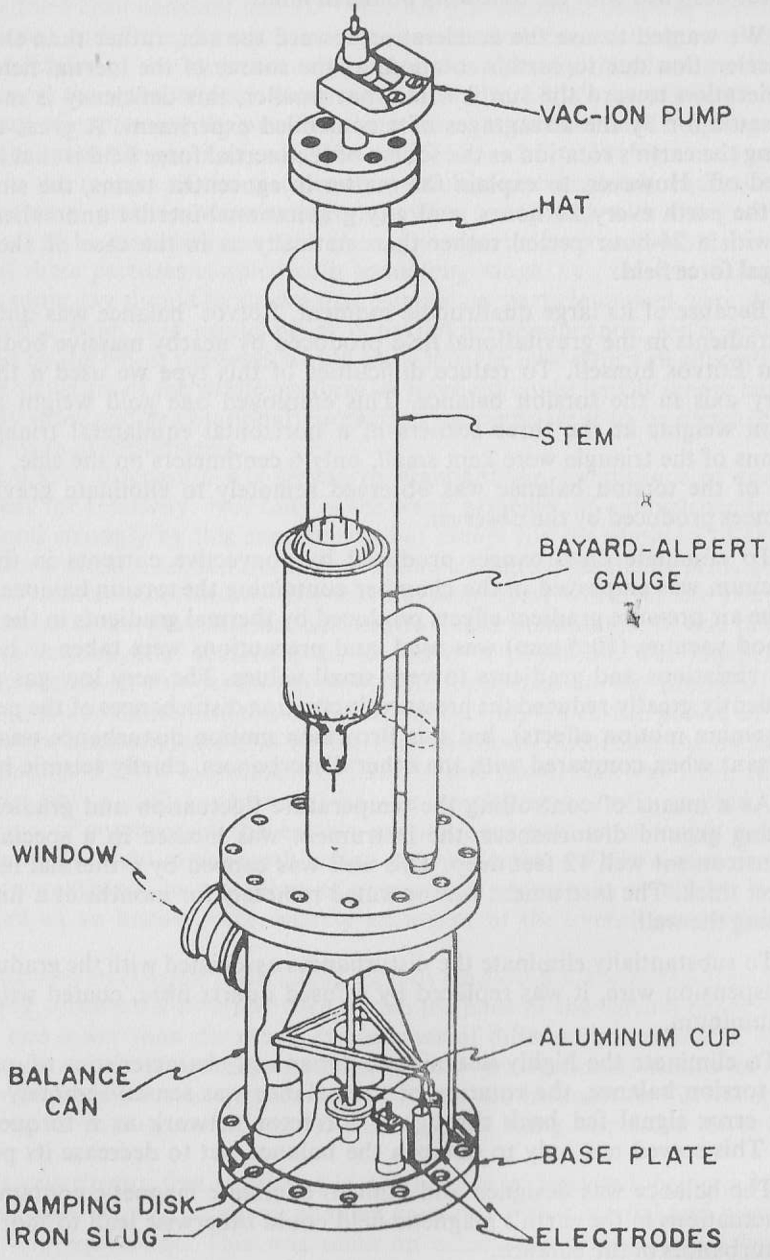

Fig. 1

(i) The data were recorded continuously and automatically and analyzed statistically on an electronic computer.

(j) A number of temperature and temperature gradient measurements could be made in the well remotely. Two of the temperatures were continuously recorded.

A schematic view of the torsion balance is shown in Fig. 1. Note the smaller gold weight between the two copper electrodes used to apply feed back torques to the balance.

The basic features of the principles of operation are easily seen by considering the situation at 6:00 a.m. with the apparatus so oriented that the mirror faces south, i.e., the gold weight is toward the north. It is evident that the gravitational pull of the sun on the gold weight tends to rotate the balance clockwise but that this is balanced by the inertial reaction force in the coordinate system in which the apparatus is stationary. A similar balance exists for the two aluminum weights. If the balance should not be exactly the same for aluminum and gold, a small excess force would act on the aluminum or gold causing the balance to tend to rotate. Assume for purposes of discussion that the gold weight should accelerate toward the sun slightly more than the aluminum. Then the balance would tend to rotate clockwise. At 6:00 p.m. the situation is reversed and the rotation should be reversed. Thus not only is a 24-hour period required for a significant effect, but the phase must be correct. As a test on any observed 24-hour effect, the whole apparatus could be rotated through 90°, 180°, or 270°, and a new set of observations taken.

It is necessary to say a few words about the necessity for electronic damping of the balance. With a completely linear device this should not have been necessary, as the response of the balance to disturbances at its resonance frequency (0·00243 sec^{-1}) is irrelevant. Its response at a frequency of 24^{-1} hr.^{-1} is all that matters to the experiment. Actually because of non-linear effects, such damping is very important. When any vibration mode of the balance is strongly excited, second order effects start to appear, and these effects tend to change the effective zero of the apparatus. As these excitations will change with time, the effect on the zero is an unpredictable fluctuation and is a severe limit to the accuracy of the experiment. It is consequently necessary to keep all the normal modes of the pendulum from being strongly excited. In the case of the torsion mode the problem is particularly severe, as the frequency of this oscillation is so low that any disturbance of the rotation of the pendulum is apt to last a very long time without damping. If one were to assume a Q of the suspension fiber of 10^5, a strong excitation of oscillation of the torsion mode would persist for 2 years. Thus any strong disturbance, localized in time, such as an earthquake, blasting, etc., would strongly disturb the pendulum, and this disturbance would not disappear for a long time.

In similar fashion the swinging mode of the pendulum, various rocking modes, as well as the fiber stretching vibrational mode, when strongly excited would give a spurious deflection to the torsion balance. This was particularly apparent after an earthquake or other seismic disturbance. Fortunately the Q's of these higher frequency modes were not so high as to lead to very long damping times, hence objectionable troubles. The torsion mode electrical damping shortened the damping time of this mode sufficiently that there was also no trouble from this cause.

It was important to be able to detect an extremely small rotation of the torsion balance ($\sim 10^{-9}$ rad.) without disturbing the balance. This was accomplished by a

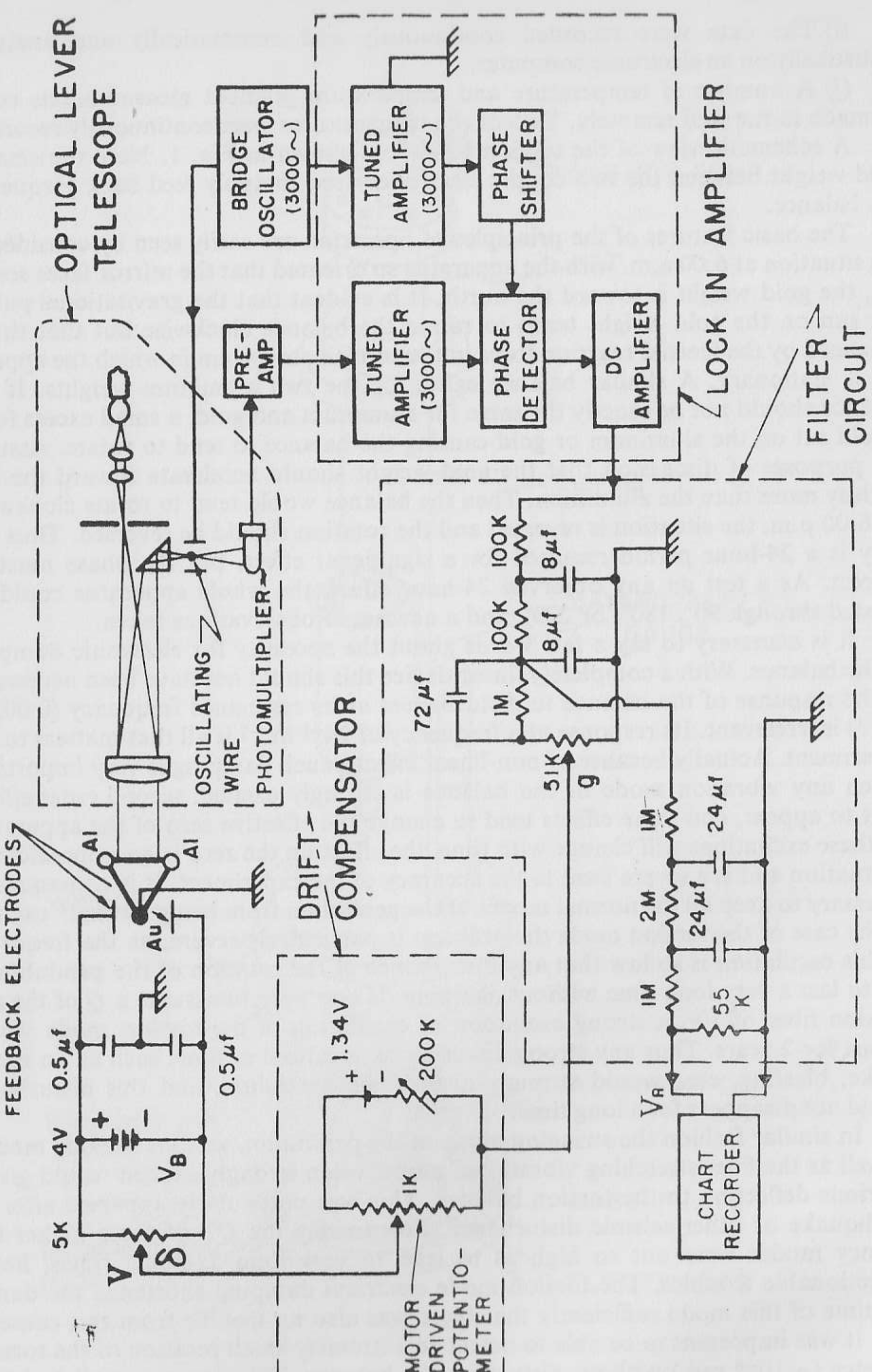

Fig 2

very weak light beam reflected from the mirror. The apparatus used is shown schematically in Fig. 2. Light from a narrow slit is collimated by a telescope objective, reflected from the optical flat polished on one face of the quartz triangle of the torsion balance, a mirror (0·25 cm × 5·5 cm), and reflected back through the objective to form a real image. This image is caused to fall upon a wire of about the same width as the slit image. The light transmitted by the wire falls upon a photo multiplier. The wire is caused to oscillate back and forth across the slit image. If the image is centered perfectly only even harmonics of the oscillation frequency appear. However, if the image is displaced slightly to one side, the fundamenal frequency appears in the light intensity. By multiplying the output voltage of the photo multiplier by the fundamental modulation frequency of the wire, a D.C. voltage is developed whenever the fundamental frequency is present in the light output. Its magnitude and sign depend upon the amount and direction of the displacement of the slit image relative to the wire. This voltage after suitable filtering is applied to the electrical system as shown in Fig. 2 to restore the pendulum to its zero position. The voltage necessary to restore the pendulum to its zero position is recorded as a measure of the torque acting on the balance.

Table I gives the chief results of this series of measurements.

It is concluded that aluminum and gold fall toward the sun with the same acceleration, the accelerations differing from each other by at most 1 part in 10^{11}.

TABLE I

Principal results of the torsion balance measurements of the difference in passive gravitational-to-inertial mass ratios.

Balance A	Weights B	Direction of Telescope	Number of Runs N	Mean value of $\eta(A, B)$[a]
		North	20	[b] $(2{\cdot}2 \pm 1{\cdot}4) \times 10^{-11}$
Gold	Aluminum	South	18	$(0{\cdot}4 \pm 1{\cdot}5) \times 10^{-11}$
		North + South	38	$(0{\cdot}96 \pm 1{\cdot}04) \times 10^{-11}$
Copper	$PbCl_2$ + pyrex flask	—	5	[c] $(0 \pm 1{\cdot}4) \times 10^{-10}$

[a] $\eta(A, B) . \equiv . \dfrac{(M^A/m^A) - (M_B/m_B)}{\frac{1}{2}[(M^A/m^A) + (M_B/m_B)]}$,

where M represents passive gravitational mass and m represents inertial mass.

[b] The results quoted for the gold-aluminum torsion balance are the means of N measurements ± the probable error of the corresponding means.

[c] The results quoted for the copper—$PbCl_2$ torsion balance represent the root mean square noise level at a frequency of (1/24 hr), averaged for the five data runs made. The five runs were made with three different orientations of the telescope, and in no case was the 24-hr fourier amplitude observed to exceed the general noise level in the frequency range near (1/24 hr).

Space Isotropies

The next null experiment requiring discussion is that on spatial isotropy performed by Hughes, Robinson and Beltran–Lopez[6], and independently by Drever[7]. This experiment has an interesting history. Devised as a test of Mach's principle, in accordance with the suggestion of Cocconi and Salpeter[8], in the opinion of the author[9] it has little to say about this principle directly, but it is equally important for another reason. It is important, as it constitutes an extremely severe test of the local isotropy of space and this imposes a strong condition on any theory of gravitation. To state the matter more carefully, any zero mass Boson field is capable of yielding quasi-static interactions between matter. However, the tremendous precision of the Hughes–Drever experiment sets precise conditions on these fields namely, they must be such as to permit a choice of coordinate system for which physical laws appear locally and spacially, isotropic.

It is important to remember that it is a property of general relativity that a coordinate system may always be chosen to be locally Minkowskian. For this choice of coordinate system, in the absence of an externally produced electromagnetic field and with the assumption that second derivatives of the metric tensor are sufficiently small, the laws of physics are spacially isotropic, i.e., invariant under arbitrary rotations of the whole laboratory relative to this space. However, inasmuch as the result of any experiment is an invariant, depending only upon the relation of the apparatus to the measured system, the fact that isotropy exists in one coordinate system is sufficient to show that for any coordinate system, phenomena observed in the laboratory should be independent of the orientation of the laboratory relative to the distant matter of the universe.

In the Hughes–Drever experiment to be described, because of the earth's rotation, the orientation of the laboratory changes with time. An extremely sensitive test of possible effects of this change in orientation is devised.

It is clear from the above that the null result of the Hughes–Drever experiment constitutes a severe *necessary* condition to be satisfied, but this does not imply that this is the only relativistic theory of gravitation compatible with the condition of local isotropy. In order to see more clearly the nature of the condition imposed on gravitational theory by this experiment, we must first broaden substantially the class of possible relativistic theories and then investigate the conditions imposed on this larger class by the Hughes–Drever experiment.

It is well known as a result of the investigations of Rosen[10], Gupta[11], Feynman[12], and Thirring[13] that the gravitational field can be treated within the framework of ordinary Lorentz invariant field theory as an ordinary zero-mass, chargeless tensor field. The interaction of matter with such a tensor field affects the matter, modifying it in such a way as to cause dilation of meter sticks and change of clock rates. As a result, such rods and clocks, made out of ordinary atoms interacting with such a field, do not provide a measure for the basic Minkowski tensor of this theory. This Minkowski tensor now becomes superfluous being replaced by the field tensor g_{ij} as the new metric tensor of the space.

Two things are clear from these papers. One is that the assumption of the Lorentz invariance of the theory is superfluous, for the Minkowski tensor is superfluous. Second, there is the implication that the gravitation may be, but need not be, considered as space geometry. It should be remarked parenthetically that in place of the Lorentz invariance of the theory associated with the original Minkowski tensor there is the usual local Lorentz invariance of a formalism based on the Riemannian metric tensor.

To recapitulate, a conclusion which can be obtained from these investigations is that the gravitational field can be, if desired, considered as a long range field interaction which affects rods and clocks, and hence the geometry measured by these rods and clocks. To interpret the gravitational field as an ordinary tensor interaction is a non-trivial re-interpretation for it opens the possibility of there being more than one long range interaction between neutral bodies, and it now becomes meaningful to consider other fields as contributing to the phenomenon we know as gravitation. As will become clear later the Hughes–Drever experiment sets a severe limit to possibilities of this type.

It may be desirable to say a philosophical word to the experts concerning this generalization. To the specialist working for years on general relativity, the Riemannian space of general relativity has gradually assumed a real and concrete form that belies its somewhat arbitrary character. Experts should be reminded of the remarks of Reichenbach, and of Poincaré before him, that the metric of a geometry is only in part a property of the space. It is equally a property of the particular type of measurement employed in the space. (Even the construction of the word "geometry" suggests that only half of this two part word "geo-metry" relates to the space, the remainder referring to its measurement.) To the extent that means of measure are arbitrary, the metrical properties of space are arbitrary.

Poincaré remarked that if surveying measurements showed space to be Riemannian, one could with equal right regard the space as flat and the meter stick distorted. This is a 3-dimensional nineteenth-century analogue of the Thirring calculation.

The general relativist accepts the general covariance of the theory as a necessary requirement because of the arbitrariness of the choice of coordinate system. However, usually he does not require a covariance associated with an arbitrariness in the choice of units of measure. Conformal transformations[14,15,16] induced by a redefinition of units, and for which units of length, time, and reciprocal mass are multiplied by a common, coordinate-dependent scale factor, constitute a restricted class of transformations of this type.

It is sometimes asserted that there is only one possible type of spatial measure in general relativity, and only one geometry, that given by ordinary meter sticks and clocks (or equivalently a measure based on the assumption of geodesic motion of neutral particles and null geodesics of light rays). However, it is possible to find counter examples and to give many alternative, if clumsy, definitions of the units of measure.

To give one example (a scale factor a function of the locally measured value of the scalar Maxwell invariant) could be applied locally to units of length, time, and reciprocal mass. As mentioned above, the resulting transformation of the metric tensor is conformal. Note that the scalar curvature is not invariant under such transformation.

While it could be argued with justification that these other arbitrarily defined systems of units are contrived, and of lesser importance than the usual one, which is very small compared with the first (since $\lambda \ll m$). Hence a very small anisotropy in the pion field is sufficient to compensate for the presence of this second term. Consider the two terms in equation (29) at relativistic velocities.

The denominator of the second term of equation (29) is the square root of a quadratic form in u^i. Consider the value of this denominator as a function of the 3-vector u^α, $\alpha = 1, 2, 3$. The possibility that it goes uniformly to a finite value as $u^\alpha \to \infty$ can be excluded, as this would require that h_{ij} be η_{ij} to within a constant factor. Also there may or may not be 2 dimensional surfaces on which the denominator vanishes in the finite space. If such surfaces exist, they bound non-physical regions of u^α space in which the denominator is imaginary. We can now consider two cases depending upon whether or not such surfaces exist. If they exist there are vales of u^α for which the second term in equation (29) is large compared with the first. On the other hand, if they do not exist, the second term vanishes uniformly in comparison with the first as $u^\alpha \to \infty$.

We may safely assume that in the first case, when the second term in equation (29) is large, the weak anisotropy of the two Boson fields is insufficient to compensate for the resulting large anisotropy in the momentum velocity relation. In the second case, the momentum anisotropy disappears as $u^i \to \infty$, whereas that of the fields does not. Apparently an anisotropy (in principle observable) should occur if an atom interacts with two zero-mass tensor fields.

It is necessary to remark that h_{ij}, generated by a spherical universe, would be expected to be diagonal with the space-like components all equal in a coordinate system exhibiting this symmetry. In this case the spatial anisotropy is missing except for the small contributions from nearby matter. On the other hand, this spatial isotropy is destroyed by a Lorentz transformation and there should be observable effects on the earth, assumed to be moving relative to this coordinate system.

To summarize this discussion we can say that the Hughes–Drever experiment appears to exclude a coupling to two zero-mass tensor fields (cosmological in origin). If two fields are present with the one strongly anisotropic, in a coordinate system chosen to make the other isotropic, the strength of coupling to one must be only of the order of 10^{-22} that of the other. If some cancellation of this anisotropy should occur through an appropriate anisotropy of the other fields, this cancellation would be expected to be incomplete, depending upon the state of the nucleus. If both tensor fields should be isotropic simultaneously, this condition would be destroyed by Lorentz transformation. Hence on the moving earth with ever changing velocity, anisotropy would be expected at some season. We conclude that the presence of a second tensor field is very unlikely in view of the experiments of Hughes and Drever.

The Ether Drift Experiments

The remaining null experiments requiring discussion may be crudely labeled as ether drift experiments, for the prototype of these experiments was that of Michelson and Morely, which was motivated by the nineteenth century ether concept.

One might rashly judge such experiments to be antirelativity in conception, but such is far from the case. There is a definite observable difference between a laboratory moving with respect to the universe and one which is not. Namely, in the first case galaxies are *observed* to stream toward us in one direction and away from us in the opposite direction. Any non-scalar field generated by this distant matter, in addition to the basic gravitational tensor, could produce motional effects. Consider a non-gauge-invariant vector field which couples with matter so weakly as to be compatible with the Eötvös experiment but which, for some reason, is strong as a component of the cosmological background. In the comoving coordinate systems for which the universe appears everywhere isotropic, this vector field must have only one non-zero component D_4 which is a function of x^4 only and hence for which $F_{ij} = 0$. Such a field could not introduce a guage invariant interaction, but there, are many coupling schemes which are not gauge invariant, e.g., $(A_i U^i D_j U^j)^{1/2}$, representing a joint interaction of a charged particle with an electromagnetic field and this cosmic field. It is easily seen that the motion of the laboratory with respect to such a vector field could lead to observable effects: positive results for an experiment such as that by Michelson and Moreley.

Of the various null experiments of this type, the most interesting and one of the most precise was carried out recently by a Princeton student, K. Turner[24], under the supervision mainly of Prof. H. Hill. It is particularly interesting, as it incorporates nuclear forces, strong electromagnetic forces in the nucleus, the electron structure of the atom, and the propagation of photons as ingredients which could conceivably disturb the null result.

While this is the most interesting of the null experiments of this type, it has not yet been published and consequently has had no publicity. In view of its importance, I am happy to take the opportunity to say something about the experiment. (Has since been published, *Phys. Rev.*, **134**, 252 (1964).)

It started out about September 1959 as an attempt to measure the gravitational red shift using the Mössbauer effect which had just been discovered, but it soon became apparent that there were two other groups working on this problem, and to avoid a horse race it was dropped about November in favor of the one to be described.

In this experiment, a cobalt 57 source was placed near the rim of a standard centrifuge wheel, roughly 25 cm in diameter, with an iron 57 absorber near the axis, the line joining the two passing through the axis but making an angle with it of about 60°. At the point of intersection on the axis, above the wheel, a thin sodium iodide scintilator was mounted on the wheel. The light from the scintilator was carried through a lucite light pipe, fixed to the wheel, to a non-rotating photomultiplier mounted above the wheel. The pulses from the photomultiplier were separated by a single channel analyzer into two categories representing the 14·4 kev. γ ray (narrow) and the broad 122 kev radiation. These two types of γ ray counts were chaneled into four groups of two scalers each to count both γ rays simultaneously in each of four quadrants of the wheel's position.

As the wheel rotated, four tiny mirrors on its periphery were used to operate electronic switches to channel the counts occurring in each 90° of rotation into separate channels. Thus, the two scalers into which counts were dumped in the first 90° of rotation of the wheel totaled up for this same quadrant all the counts accumulated in a long period of counting.

We shall now describe the experiment. For simplicity in thinking about the problem we shall concentrate on only one aspect of it, and mention other aspects later. Consider the nucleus to be thought of as a clock. If its proper clock rate is a function of its velocity relative to the distant matter of the universe, it would be expected to vary in lowest order quadratically with the velocity. This is made a meaningful statement by making the comparison with a fixed clock of the same type using light pulses for the intercomparison.

This is effectively what the apparatus does. With the assumption that the electronic structure behaves in a proper Lorentz-invariant way and that light propagates on null geodesics, the γ ray from the source at the rim of the wheel may be compared directly with the absorber near the axis, after making allowance for the second order Doppler shift.

The second order Doppler shift is actually important for the experiment. Because of this effect the radiation from the source is red shifted substantially, and the probability of transmission through the filter varies linearly with any further shift (very small). If it were not for the initial shift induced either by the Doppler effect, a temperature difference, or some other cause, the effect would be quadratic in the frequency shift, hence unobservable.

Because of the velocity $\mathbf{u}$ of the laboratory relative to distant matter, the Mössbauer clock at the rim of the wheel has a time varying velocity $\mathbf{u} + \mathbf{v}$, and the clock rate should vary with the angular position of the wheel as

$$\frac{\delta\omega}{\omega} = 2\gamma uv \cos\theta. \tag{21}$$

Here v refers to the peripheral speed of the wheel, and the angle θ is that between the source velocity vector and the component of $\mathbf{u}$ lying in the plane of the wheel. The magnitude of this component is designated by $\mathbf{u}$. The γ is some small dimensionless number, a measure of the magnitude of the effect, if any.

As the wheel rotates, counts are accumulated for each of four quadrants, and the ratio of the 14·4 kev counts to the 122 kev counts is taken to be a measure of the shift $\delta\omega/\omega$ (averaged over that quadrant). The actual numerical relation between change in count ratio and $\delta\omega/\omega$ is easily obtained from the known line width and shape, after including the shift due to the second order Doppler effect.

The best data were obtained from 134 runs of about 10-minute duration taken at various times of the day between October 24, 1961, and November 11, 1961. This represented a total of 4×10^6 14·4 kev counts and 5×10^7 122 kev counts.

As the earth rotates, any effect of a component of $\mathbf{u}$ lying in the equatorial plane of the earth would rotate spatially relative to the laboratory producing an anomaly, the axis of which would rotate in the laboratory. By making a least squares fit to the expected time dependence of the anomaly, it was possible to give γ a value

$$\gamma < 4{\cdot}2 \times 10^{-5} \tag{22}$$

with the assumption that the component of $\mathbf{u}$ in the equatorial plane is 200 km/sec with an unknown direction. The assumption of 200 km/sec is of course arbitrary, but it is reasonable. The random motions of galaxies are of this order, as is the motion of the sun inside our own galaxy. Another way of describing the result is to quote γu, which gives 840 cm/sec as an upper limit on this, the classical "ether drift velocity."

Inasmuch as both photon propagation and the mechanical structure of the wheel were involved in this experiment, it also sets limits on possible anomalies in these parts of the apparatus. The analysis would be very similar to that of the effect on the proper clock rate.

II. Three Famous Tests of General Relativity

The Gravitational Red Shift

As discussed above, this is not a test of anything but energy conservation and mass-energy equivalence. While it is possible with a second tensor interaction to violate the mass-energy equivalence,[18,19] the Hughes[6]–Drever[7] experiment seems to exclude this.

While this experiment may not be the most important of relativity experiments, it is interesting, and I should like to discuss briefly the experiment of one of my students, J. Brault, on the red shift of solar lines.[25]

This subject has had a long and checkered career going back to the earliest days of general relativity. After some early misguided enthusiasm, it soon became clear that the solar spectral lines did not give the expected red shift (some were actually blue shifted). One particularly annoying feature of the red shift was that it was strongly dependent on how close to the limb of the sun one observed. At the center of the sun the shift tended not to appear, although different lines gave different shifts. At the limb the shifts tended to agree better with expectations.

At first these shifts were explained as pressure effects, with the shifts being larger at the center of the sun because the lines were formed deeper in the atmosphere. It became clear finally that the center-limb shifts were primarily due to the Doppler effects associated with the convective transport of heat out of the sun. Deep in the sun this energy is transported by radiation, but it is convectively transported in the outer part until near the surface, insofar as the sun can be said to have a surface, it is again transported by radiation. The Doppler effect of the hot rising columns and cool falling gas leads to the irregularly shifted lines.

While the astronomer's knowledge of the surface of the sun improved enormously in the past forty years, the determination of the red shift, worked on almost constantly by different spectroscopists during this period of time, improved very little.

In my opinion this lack of progress was largely due to their use of the wrong instrument. The photographic plate is a wonderful device for conveniently recording a lot of information on a small plate but is dreadful at providing a quantitative measure of light intensity. In the language of the experimentalist, it has poor "signal to noise." Because of this poor intensity discrimination due to grain, lack of plate uniformity, lack of development uniformity, and other causes, these classical techniques were incapable of giving a precise measure of the center of a broad line unless it showed a narrow "core."

We made the assumption that a very broad spectral line would be developed in the solar atmosphere above the main convective troubles, and hence be free of systematic Doppler shifts. (It should be remarked that the "wings" of the line would still be developed deep in the sun and that they would be expected to experience strong Doppler shifts which would not average to zero). Dr. Brault was able to show that with the proper spectrometer, averaging over reasonably large areas, the line position of a strong line agreed with the expected value and did not show any noticeable center-limb shift.

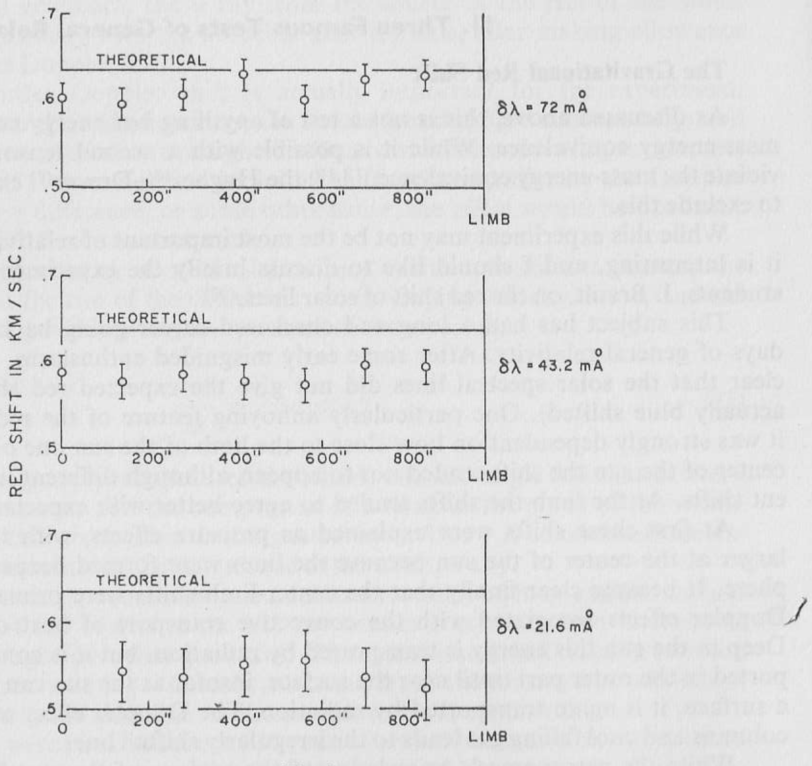

Fig. 3.

It occurred to us that the sodium *D* lines were ideally suited for the red shift measurement. The lines were strong; sodium had a good abundance; it was easily ionized at high temperatures removing this part of the sodium from the game; thus, the rapidly moving very high temperature parts of the upper atmosphere should not contribute.

The ideal line for this purpose was found to be the D_1 line of sodium.

In order to measure with precision the center of the line, a special instrument was required. This was designed and built by Dr. Brault and it worked beautifully. It consisted of a two-pass grating instrument employing three slits, the third one of which was broad, designed to remove ghosts (false lines). The middle slit could be displaced and oscillated by an electromechanical device. The light was detected by a photomultiplier, and the line center was defined by the requirement that the slit

oscillation frequency disappear from the output voltage of the photomultiplier whenever the mean position of the slit agreed with line center. It is evident that, if the line is asymmetric, a correction is needed for the effect of the asymmetry. This can be obtained by making observations at various amplitudes of oscillation if the asymmetry is known. In similar fashion a correction for the asymmetries of the spectrometer is required.

The spectrometer, as it was designed by Dr. Brault, located electronically the line "center" and automatically locked the mean position of the oscillating slit to the line center. This line "center" was automatically recorded electronically as the image of the sun swept across the entrance slit. The raw data, uncorrected for asymmetries, is shown in Fig. 3 for 3 amplitudes of oscillation $\delta\lambda$. It should be noted that even without correction the agreement is better than 20 per cent. It should also be noted that the center-limb shift has disappeared. After correction for asymmetries the red shift was found to agree with the expected result with an accuracy of 5 per cent (noise limited). It should finally be remarked that the secondary laboratory standard used was a sodium lamp which was compared with a sodium absorption cell as a primary standard.

This appears to be one of the two best determinations of the red shift. The other is the determination by Pound and Rebka[26] using the Mössbauer effect. Its accuracy was 10 per cent.

The Gravitational Deflection of Light

The gravitational deflection of light is an observation which is more important for gravitation. This effect depends upon other components of the gravitational tensor besides g_{44}, in the usual coordinate system of the Schwarzschild problem. Unfortunately, the accuracy of this observation is poor. The analyses scatter from a deflection at the limb of the sun of 1·43 seconds of arc to 2·7″ (1·75″ computed). The scatter would not be too bad if one could believe that the technique was free of systematic errors. It appears that one must consider this observation uncertain to at least 10 per cent, and perhaps as much as 20 per cent.

The Perihelion Rotation of Mercury

The third and final one of these tests is even more important as it involves the g_{44} component to second order in GM/r and the other components to first order. Unfortunately, it also is uncertain. This is because of an uncertainty in the gravitational quadrupole moment of the sun.

On the surface this check appears to be very satisfactory. The most recent results are the following[(27)]:

	Mercury	Venus	Earth
Observed	43″·11 ± ·45	8″·4 ± 4·8	5″·0 ± 1″·2
Calc.	43″·03	8″·3	3″·8

These are perihelion rotations in seconds of arc per century. In saying that these are observed effects it is necessary to remark that what is observed is far larger. The observed rotation is 120 times as great for Mercury, 600 times as great for Venus, and 1200 times as great for the Earth. From these large effects it is necessary to subtract the geometrical effect of the general precession of the equinoxes and the effects of planetary perturbations. It is only a small residual that is to be compared with the calculated relativistic effect.

Unfortunately, only the planet Mercury provides a sensitive test of this relativistic effect. The interaction with Venus was, and may still be, the largest source of uncertainty in the non-relativistic perturbation of Mercury's orbit. Venus does not have a satellite, and its mass can be determined only from its perturbations of other planets, such as Mercury. Obviously, this is a somewhat circular argument if we must first use the perturbations to determine adopted planetary masses and then use these masses to calculate orbits.

The uncertainty concerning the mass of Venus seems recently to have been reduced substantially by the Venus fly-by of the American planetoid. The orbit was sufficiently accurately determined to permit a better determination of the mass of Venus. This substantially reduces the possibility of a serious discrepancy in this adopted mass. Hence, it appears that we must accept this "observed" result if the only substantial perturbations are due to other planets.

Let us consider other possible sources of matter for a perturbation of Mercury's orbit. These have been considered as long ago as 1928 by J. Chazy(28). The solar corona could not have enough matter to be important without scattering more light. The matter responsible for the zodiacal light, assumed to be meteorite-like bodies, is not sufficient. For the same scattering of light, dust is even less effective in perturbing the orbit. The way to get the most matter for the least scattered light is to put it into one body.

The size of body required, near the sun, is so great as to be visible. It appears that matter exterior to the sun sufficient to be important is not easily found. Actually, these old discussions should be reexamined, particularly the possibility of a few small asteroid bodies near the sun. The reason for this is the following: If gravitation is due to a combination of a tensor and scalar interaction, the expected perihelion rotation is somewhat less. Even a 5 per cent decrease would be significant and interesting. The classical considerations were concerned with explaining the whole discrpancy. We are concerned with the possibility of a discrepancy of the order of 5–20 per cent.

There is one possible source of discrepancy which seems to be very serious. A solar flattening amounting to a decrease of the polar radius by only 0·1″ of arc relative to the equatorial radius would result in a non-relativistic contribution to the rotation of 8·3″ arc per century, 20 per cent of the relativistic effect. It must be said in making this statement that it is assumed that the visual surface of the sun represents an equal pressure surface which is also assumed to be an equipotential surface for the gravitational field. If these assumptions are valid, the gravitational field is known everywhere outside this photosphere, once its shape is known.

It must be recognized that there are uncertainties about these assumptions. First, a small variation in brightness of the photosphere in the vicinity of the pole relative to the equator would modify the connection between isophote lines and equipressure surfaces. Second, it is only in the absence of shear stresses and velocity field gradients at the surface that the equipotential surface is identical with the equipressure surface.

Magnetic fields are capable of exerting shear stresses, and velocity fields are known to exist. Both of these effects appear to be minor but a close study will be necessary before one can be sure.

It appears that the interior of the sun is not so well known that a solar flattening as large as 0·1″ arc, $\Delta\gamma/\gamma \sim 10^{-4}$, can be excluded. This could be produced by a rapidly rotating core in the sun, or by toroidal magnetic fields, which are capable of large stress but are not seen at the surface.

It is now necessary to say a word about the possibility of observing a flattening as small as 10^{-4}. This appears to be definitely measurable, but not with the classical techniques of the astronomers. The bad daytime seeing smears out the limb of the sun by several seconds of arc and we are interested in only 0·1″ arc. An experiment has been started at Princeton to attempt to set limits on the solar oblateness but results are not yet available.

It is reasonable to ask if a quadrupole moment of the sun would not have other effects on the planets besides rotation of their perihelions. Here we have been very unfortunate. A flattening of only 10^{-4} (0·1″ arc) has no other effects presently observable. The axis of the sun is tipped only 3·3° with respect to the plane of Mercury's orbit. The resulting torque is small but is sufficient to produce a slow wobble of the orbit. This leads to the expectation that the inclination of Mercury's orbit would decrease anomalously by 0·16″ of arc per century (for a flattening of 10^{-4}). This apparently cannot be excluded by the observations, for an anomalous decrease of about this size is known, but with comparable probable error.

Unfortunately, we are also unlucky with respect to Venus' orbit. Here again the effect is small, even smaller because the planet is farther out. The angle between the normal to the orbital plane of Venus and the rotational axis of the sun is about 4°. Here the effect is almost completely one of producing a small anomalous motion in the node of Venus.

By the time we reach the earth's orbit the inclination of the sun's axis is a full 7°15′, but we are now so far out that the effect of this coupling is very small. We are forced to conclude that there is not yet believable observational evidence that can be used to exclude a discrepancy as large as 10–20 per cent in the relativistic part of the perihelion rotation of Mercury. It seems very unsafe to argue on the basis of theories of the sun's interior that an oblateness as large as 10^{-4} is impossible.

It is unfortunate that both the light deflection and perihelion rotation observations are so uncertain, for these are the only data which could be used to exclude gravitational theories incorporating both scalar and tensor fields(21). In the Brans–Dicke theory, a value of the constant $\omega \geq 2$ now seems possible with the new large uncertainty in the perihelion rotation.

Cosmic Experiments

There are literally thousands of observations of geophysical and astrophysical nature which might be used to exclude a theory such as that discussed in Ref. 21. However, it is virtually impossible to use this type of data to "prove" such a theory. Of course, one never proves a theory with an experiment, for a better experiment can always prove it wrong. However, astrophysical and geophysical data are particularly suspect, for the earth, the solar system, a star, and the galaxy are all too complicated to be used to support strongly a physical theory. There are too many loopholes in the form of alternative explanations.

On the other hand, a physicist ignores such data at his peril, for they can supply him with useful ideas including, perhaps, a fairly convincing reason for dropping the theory.

We make no attempt here to rediscuss those questions which are taken up in Appendices (9), (10), (11), and (12).

Summary and conclusion. The following point of view was adopted: For purposes of discussing relativity experiments, one should consider a somewhat wider theoretical framework than one would normally like, and experiments should be used to limit this class of possible theories.

In this connection it was found helpful to treat gravitation as a particle field, and to subordinate the geometrical interpretation. The possibility that the gravitational effect could be due to two or more long range fields was considered. The following points occurred:

(1) The primary gravitational effect is, perhaps, due entirely to a zero mass tensor interaction if Mach's principle is valid; for the inertial forces are acceleration dependent and a Lagrangian quadratic in the velocity is needed for acceleration terms to appear in the Euler equations.

(2) A tensor plus vector theory of gravitation seems unlikely because of the precise null result of the Eötvös experiment.

(3) A two-tensor theory of gravitation can be excluded by the Hughes–Drever experiment.

(4) A tensor plus scalar field affecting the fine structure constant or other strong coupling constants can be excluded by the Eötvös experiment.

(5) A tensor plus scalar field coupled to the weak coupling constant cannot be excluded.

(6) A tensor plus scalar coupled to only some types of particles can be excluded by the Eötvös experiment.

(7) A tensor plus scalar coupled in the same way to all kinds of particles cannot be excluded.

(8) A tensor plus scalar interacting with each other but not with other particles cannot be excluded.

(9) The theories of the tensor plus scalar types (Jordan) cannot be all excluded easily. They violate only the light deflection and perihelion rotation effects, and these observations are too poor to represent strong results.

In conclusion, there is a real challenge for the experimentalist to exclude or else to find the scalar component of the gravitational field.

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Appendices

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Appendix 1

Experimental Tests of Mach's Principle*

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In this note it will be shown that, contrary to the suggestion of Cocconi and Salpeter,[1] the extremely precise null result of the experiments of Hughes, Robinson,

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