To Info. Div.

UCRL 3540 - Rev
c.8

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

BERKELEY, CALIFORNIA

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UCRL-3540 Rev

UNIVERSITY OF CALIFORNIA
Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

EXPERIMENTAL VERIFICATION OF THE "CLOCK PARADOX" OF RELATIVITY

Frank S. Crawford, Jr.

October 24, 1956

Printed for the U. S. Atomic Energy Commission

EXPERIMENTAL VERIFICATION OF THE "CLOCK PARADOX" OF RELATIVITY

Frank S. Crawford, Jr.

Radiation Laboratory
University of California
Berkeley, California

October 3, 1956

ABSTRACT

An experiment is proposed to test the "clock-paradox" prediction of relativity. The experiment as proposed involves accelerator-produced pi mesons and is relatively easy. It is then shown that the proposed experiment has already been carried out with cosmic-ray mu mesons through the four combined experiments by Rossi, Hilberry, and Hoag; Rasetti; Blackett; and Ticho. Their results verify the asymmetric aging predicted by relativity.

EXPERIMENTAL VERIFICATION OF THE "CLOCK PARADOX" OF RELATIVITY

Frank S. Crawford, Jr.

Radiation Laboratory
University of California
Berkeley, California

October 24, 1956

Einstein's theory of relativity predicts that if one of two twin brothers leaves home in a space ship and spends a considerable amount of time traveling at high velocity with respect to his home inertial frame, then, when the traveler returns home, he will find himself physiologically younger than his stay-at-home brother, and his pocket watch will have performed correspondingly fewer revolutions.

A simple description of the trip can be made in the home inertial frame, which is in uniform motion with regard to the distant stars. In order to guarantee the above prediction, three assumptions are sufficient:

1. The time dilation of special relativity holds for uniform motion.

2. The acceleration of an ideal clock relative to an inertial system has no influence on the rate of the clock, and the increase in the proper time of the clock at any time is the same as that of the standard clocks in the system in which the clock is momentarily at rest.[1]

3. The traveler and his pocket watch are good approximations to an ideal clock. (The accelerations must not kill the traveler or break his watch.)

The description of the trip from the point of view of the traveler's (noninertial) rest frame is complicated by the accelerations. This complication has led historically to the name "clock-paradox result" for the above prediction of asymmetric aging. The "paradox" can be "resolved" (i.e. a consistent description can be made in the traveler's rest frame) by the use of general relativity.[2,3] Tolman's derivation is especially simple, and shows that both brothers come to the same conclusion, viz., that the traveler ends up younger than the stay-at-home. (It has been pointed out to us that one need not use general relativity to describe the trip from the traveler's accelerating frame. Special relativity plus Assumptions 2 and 3 is sufficient.[4])

An experimental test would be highly desirable, because (a) there is still some disagreement as to whether or not relativity actually does predict the asymmetric aging,[5] and (b) Assumption 2 does not follow from special relativity.[1] Verification of the "clock-paradox result" would therefore require that Assumption 2 be included in any correct generalization of special relativity.

Before describing the proposed experiment, we will show that if special relativity is assumed to be correct, it is not necessary for the traveler to make a complete round trip. He can make a one-way trip, stop at his destination, and then compare his age with the stay-at-home twin by means of radio signals. This follows from the basic assumption of special relativity that a common time can be defined everywhere in a given inertial frame (the home frame) by use of local clocks that have been synchronized by means of light signals.[6] The traveler can always compare his pocket watch with a local clock at his destination, after he is at rest in the home frame. As an additional check, he could then return home at a comparative snail's pace, and compare his pocket watch once again with that of the stay-at-home brother. He would find that the age difference acquired during the fast outward trip is maintained unchanged during the return trip, provided that the traveler's return velocity is small enough. This follows directly from the fact that

$$(c/v)\,[(1-v^2/c^2)^{-1/2}-1] = 1/2\,(v/c) + \ldots$$

goes to zero as $v/c \to 0$. (In this second check we are using the implicit assumption that we can synchronize clocks at different places in an inertial frame by carrying (slowly!) a clock from one place to another.[6] Thus, it is legitimate for the brothers to dispense with the return trip in their attempt to verify the asymmetric aging. This is an important point, since the proposed experiment involves (for practical reasons) a one-way trip.

We propose to test the predicted asymmetric aging by means of accelerator-produced π^+ mesons.[7] If we have a group of pions initially at rest in the laboratory, then from their well-known rest mean life of 2.55×10^{-8} sec for radioactive decay we can predict the average number that will remain at some later time. Conversely, we can determine the age of a group of pions by counting the number of survivors in the group, provided that we know the number of mesons at the birth of the group.

Consider two groups of mesons, initially at rest with regard to each other. We separate the two groups and subject them to various asymmetric conditions of acceleration, heat treatment, etc. We then bring the two groups to rest in a frame that is in general different from the original rest frame, and compare the number of survivors in each group. In general, if one group shows fewer survivors than the other it will not be necessary to attribute this fact to an excess aging of this group. Instead, one can usually attribute the reduced number to an excess of "violent" deaths resulting from unusual treatment. For instance, if one group passes through extra material it could suffer an excess of deaths due to nuclear collisions, which destroy pions rather than aging them. As we wish to draw conclusions about relative age from relative numbers, we must therefore treat the two groups with complete symmetry in matters that do not involve space and time alone. In addition, we must hope that Assumption 3 holds, i.e., that mesons are not too delicate to withstand the required accelerations without "breaking."

The experiment is to be performed with a uniform, parallel beam of monoenergetic π^+ mesons having a kinetic energy of (for example) 200 Mev. The beam is pulsed so that mesons emerge in bursts that are short compared with the meson mean life. The experiment uses two identical detectors. Each detector has a copper absorber just thick enough to slow the mesons down and bring them to rest in the center of a large plastic scintillation counter. The output pulses from each detector pass down coaxial cables of identical length to an oscilloscope. The oscilloscope has two display sweeps (one for each detector), which are triggered by the accelerator.

The experiment consists of two parts. In Part 1, the two detectors are placed side by side in the beam. During each beam pulse a number of π^+ mesons--say 1000--is incident on each detector. The two sweeps will each show, first, a large pulse corresponding to the stopping of the mesons in the scintillation counters. This pulse will be followed by individual pulses, as the pions decay into 4-Mev muons. The time distribution of pulses will show the characteristic 2.55×10^{-8}-sec mean life of the pion's radioactive decay, and the total number of pulses will be 1000. (We neglect as irrelevant the loss of mesons by "sudden death" nuclear collisions during the slowing down in the absorber, since this effect will cancel out.) Both sweeps will look the same, except for random statistical fluctuations characteristic of the

decay process. Here the two groups of mesons are initially at rest relative to each other, and remain at zero relative velocity during the entire experiment because they are decelerated simultaneously to rest in the laboratory. Part I is a calibration experiment.

In Part 2, detector No. 2 is moved parallel to the pion beam to a new position 30 ft to the rear of detector No. 1. The experiment is now repeated. Sweep No. 1 will show no change in its average presentation from that obtained in Part 1. Sweep No. 2 will exhibit a changed appearance. First, the "stopping pulse" will be shifted to a later time by 3.35×10^{-8} sec, the time (as measured in the laboratory system) that it takes 200-Mev mesons ($v = 0.91c$) to travel 30 ft. After the stopping pulse, individual pulses will appear corresponding to the decay at rest of the pions, exhibiting the usual 2.55×10^{-8}-sec mean life. At the time that this second stopping pulse occurs, the first group of mesons will be 3.35×10^{-8} sec old, and of the original 1000, the number left (on the average) will be

$$1000 \cdot \exp(-3.35/2.55) = 267.$$

The decay pulses of these 267 mesons will appear on sweep No. 1 at times later than that marked by the stopping pulse on sweep No. 2. Now, if there is no real asymmetric aging effect, the second group of mesons must have the same age as the first, and therefore, only 267 pulses (on the average) will appear on sweep No. 2 after the stopping pulse. But according to the prediction of Assumptions 1, 2, and 3, the internal clocks of the second group of mesons have turned through only

$$(1-v^2/c^2)^{1/2} \times 3.35 \times 10^{-8} = 2.35 \times 10^{-8} \text{ sec},$$

while the laboratory clock has turned through 3.35×10^{-8} sec, so that group No. 2 is younger than group No. 1 by 10^{-8} sec and contains

$$1000 \cdot \exp(-2.35/2.55) = 398 \text{ survivors}.$$

This will be evidenced by the appearance of 398 decay pulses on sweep No. 2, instead of 267. We thus have a large, easily measurable effect.

The experiment should be comparatively easy to perform at any one of a dozen existing high-energy accelerators, with small modifications of a practical nature. For instance, it is not easy to obtain with present techniques a pulsed meson beam of duration $< 10^{-8}$ sec, so that one would count individual mesons rather than groups. In Part 2 of the experiment, the timing function of the stopping pulse of group No. 1 could be taken over

by a pulse from a thin counter at the forward position. This counter should be made wide enough to cover both group No. 2 and group No. 1.

We now declare that the proposed experiment has actually been performed implicitly, with results that verify the prediction of our three assumptions. In the first place, physicists have "engineered" dozens of meson beams and have made explicit use of the fact that the relativistic time dilation can be "used" to enable one to bring beams out over large distances to convenient experimental areas without excessive loss of intensity through decay (aging). The first quantitative result of this type is in fact contained in the combined experiments of Rossi, Hilberry, and Hoag,[8] Rasetti,[9] and Blackett.[10] Rossi et al. measured the decrease in mu-meson flux between mountain altitudes and sea level, and by measuring and correcting for that part of the loss that was due to ionization-energy loss of the mesons in the air path, they arrived at a mean radioactive decay distance of about 9.5 km. This yields, for no time dilation, a mean decay lifetime of about 30×10^{-6} sec. From the measurements by Blackett on the momentum distribution of mu mesons at sea level, Rossi et al. deduced a mean value for $(1-\beta^2)^{-1/2}$ of about 15, from which they predicted a mean decay lifetime of about $(30 \times 10^{-6})/15 = 2 \times 10^{-6}$ sec for mu mesons at rest. Rasetti later measured the mean life of mu mesons at rest and obtained $(1.5 \pm 0.3) \times 10^{-6}$ sec. Thus Assumption 1, the relativistic time dilation for decay has been verified quantitatively. (Later measurements verify the time dilation with greater accuracy.)

The question remains whether or not these experiments verify the predicted asymmetric aging. We believe that they are necessary, but not sufficient. In the Rossi experiment, the flux is measured at two places, without appreciable deceleration of the mesons. A little consideration shows that the "twin paradox" is not even qualitatively discernible in any experiment that does not involve relative accelerations, for then the traveler never leaves home, or else never returns.

In order to complete the experimental test of the clock-paradox effect it is necessary to decelerate the mu mesons and observe their decay at rest—once at mountain altitudes (at absorber No. 1 in our proposed experiment), and once at sea level (absorber No. 2). The crucial point here is to see whether or not the number of observed decays at rest is equal to the number of fast mu mesons (of the proper energy) incident on the absorber, both at mountain altitude and at sea level. Given the

Rossi-Rasetti-Blackett time-dilation results, the only way in which nature can avoid the asymmetric aging is by causing the Group 2 (sea level) mesons to undergo anomalously large aging during their deceleration to rest in Absorber 2, such that by the time they are at rest in the laboratory they have the same age as the Group 1 mesons, which were stopped at the mountain absorber and have been decaying at the normal rate while the Group 2 mesons continued down to sea level with a time-dilated mean life. The excess aging during deceleration at sea level would be indicated by an anomalously large number of radioactive decays during the deceleration, and correspondingly fewer decays at rest from the survivors. Furthermore, the amount of anomaly at sea level depends on the height of the mountain! This peculiar behavior cannot be ruled out by special relativity alone, but is ruled out if we add Assumption 2. It is apparent that the same asymmetric aging will also result from a weaker assumption than No. 2, namely, the assumption that any aging due to acceleration alone is independent of the history of the particle. To verify Assumption 2, we must show that no anomalous aging occurs during acceleration.

This last necessary experiment has in fact been performed. Harold Ticho observed the decay of positive mu mesons that had been decelerated to rest in an aluminum absorber. The experiment was performed at 11,500 ft[11] and at 600 ft (Chicago) with the same apparatus.[12] The time (in the laboratory frame) for the Group 2 mu mesons (180-Mev average kinetic energy) to travel from 11,500 ft to Chicago level is 12×10^{-6} sec. The mean life at rest was measured as about 2×10^{-6} sec both at 11,500 ft and at Chicago. Let us consider 10,000 Group 1 mesons that come to rest in the mountain absorber; only 10,000 exp(-6)= 25 survive by the time the Group 2 mesons reach Chicago level. Of 10,000 fast Group 2 mesons passing the mountain absorber, 10,000 exp(-2.2)= 1100 arrived at the low-altitude absorber. In Ticho's experiment, fast incident muons trigger the counter system; delayed counts due to radioactive decay at rest are then observed. From the known momentum spectrum of the mesons at sea level and at mountain altitude, and the calculated geometrical efficiencies, Ticho can predict the number of fast muons that should stop in the absorber AT EITHER PLACE and register their decays, provided that nothing "unexpected" is left out of the calculation. From the above numbers we see that if Ticho observes the expected number of decays at rest at 11,500 ft, then, if there is no asymmetric aging, he must observe

at Chicago a rate anomalously reduced by a factor of 1100/25= 44. Instead, Ticho observed roughly the expected number of decays at rest, both at low altitude and at high altitude. (In fact, his Chicago-level measurement of the mean life would have been practically impossible if the decay counting rate had been reduced to 2% of that expected!)

Thus, Assumption 2 has been verified.

We remark that in Ticho's experiment the muons are brought to rest in about 15 cm and therefore suffer an average acceleration of about 3×10^{16} g, where g = 32 ft/sec.[2] The individual ionization collisions with electrons can involve accelerations up to about 10^{12} times this average value.

We conclude that the experiment that we have proposed for testing the clock-paradox result has already been carried out, through the combined experiments of Rossi, Hilberry, and Hoag,[8] Rasetti;[9] Blackett;[10] and Ticho.[11,12] Their results verify the asymmetric aging predicted by Einstein's theory of relativity.

ACKNOWLEDGMENTS

We are grateful to Drs. Stephen Gasiorowicz, Joseph Lepore, Maurice Neumann, Wolfgang K. H. Panofsky, and Henry Stapp for illuminating discussions.

This work was done under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

1. C. Moller, The Theory of Relativity (Oxford University Press, Oxford, England, 1952), p. 49.
2. Ibid., p. 258
3. R. C. Tolman, Relativity, Thermodynamics, and Cosmology (Oxford University Press, Oxford, England 1934,) p. 194.
4. H. Stapp, private communication.
5. H. Dingle, Nature 177, 782 (1956).
6. C. Moller, The Theory of Relativity (Oxford University Press, Oxford, England, 1952), p. 31 ff.
7. The possibility of using accelerator-produced pions to verify the "clock-parodox prediction" was pointed out by E. Martinelli and W. K. H. Panofsky, Phys. Rev. 77, 465 (1950). Their method would be, even today, much more difficult technically than that proposed here.
8. Rossi, Hilberry, and Hoag, Phys. Rev. 57, 461 (1940). We would like to thank Professor Luis W. Alvarez for calling our attention to the cosmic-ray mu-meson experiments.
9. F. Rasetti, Phys. Rev. 60, 198 (1941).
10. P. M. S. Blackett, Proc. Roy. Soc. A, 159, 1 (1937).
11. H. Ticho, Phys. Rev. 72, 255 (1947).
12. H. Ticho, private communication.