HOME

Radioactive Clocks

A Basis for the Absolute Measurement of Time

By A. C. Sturt

Variations in the wavelength of electromagnetic radiation observed on Earth are a well established phenomenon. Increases of wavelength have variously been ascribed to the recession of the emitters (stars), time dilation (satellites' clocks) and gravity (the Einstein redshift). On the other hand reductions occur when light travels through transparent media such as liquids, because frequency is maintained while velocity is reduced.

At the same time wavelengths are used to define universal standards of time and length i.e. the second and the metre. The assumption is that the conditions in which measurements are made can be standardised, so that extraneous variations do not occur. But, however unlikely it is, the possibility of ambiguity must remain.

This note suggests that it might be possible to make a clock based on radioactivity which provides a unit of time that is certainly invariable and totally independent of all other phenomena i.e. an absolute unit of time. In principle it can be as accurate as patience permits, comparable to the caesium-133 clock or 1 in 10^{10}, but this depends on the development of a suitable standard of radioactive decay.

Such a clock would provide a way of investigating variations in units of time which are measured using other bases: ephemeris, sidereal, electromagnetic etc. It could also be used to elucidate the effects on light of other natural phenomena, such as gravity, distance travelled through space, velocity and so on, as it approaches its limit i.e. the relativistic effects.

A. Introduction

Radioactive decay is used to date the formation of naturally occurring materials and the manufacture of artefacts from the distant past. The basis of the method is the decay of radioactive atomic species with time. Residual radioactivity emitted per unit time is measured with a detector and a clock, and the age of the sample can then be calculated from the decay equation using the known parameters for that element. The age is therefore expressed in terms of clock units i.e. seconds, though these may be transformed into months or years etc. It must therefore contain any uncertainty in or local influence on the physical phenomenon on which the clock is based e.g. the wavelength of electromagnetic radiation. These are inherent in the standardised conditions referred to above.

However, the process of radioactive decay may itself form the basis of measurement of elapsed time. A radioactive clock need not depend on the measurement of time by using another natural phenomenon, such as electromagnetic radiation. The unit of "radioactive time" may therefore respond differently at velocities approaching the speed of light, when other clocks slow down, according to the Theory of Relativity.

If radioactive time were found to behave differently under extreme conditions, it would have profound implications for the SI Units of time and distance i.e. the second and the metre, and all that flows from them.

Clocks conventionally rely on phenomena which involve continuous repetition of events in series long enough to run in parallel with the events which are being timed e.g. the vibrations of quartz crystals, the frequencies of electromagnetic radiation, the cycles of astronomical phenomena etc to time races, processes, orbits and so on.

Repetition in the proposed radioactive clock lies in the unchanging probability of decay of a radioactive nucleus. Radioactive elements decay by a change of state of the individual atom from which a quantum of radiation is emitted. Each quantum of radiation can be made to produce a scintillation or "spark" in a detector, so that it can be individually counted. Using statistical concepts this provides the means of measuring time spark by spark in large populations of radioactive nuclei, expressed solely in terms of number i.e. the number of decay events.

Number, unlike physical phenomena, must unquestionably be constant throughout time and hence space. It must always have been constant, because it is a definition. There is no other possibility.

B. Assumptions

A number of assumptions need to be made about the process of radioactive decay. However, they are all assumptions which can be tested independently under laboratory conditions. They relate to the decay of nuclei both as individual entities and en masse.

1. **Individual nuclei**

    a. The decay of the individual nucleus is independent of other nuclei. There is no interaction between them.

    b. The presence of products of decay does not influence the decay of an individual nucleus. It is not an equilibrium process.

    c. Radioactive decay is stochastic. The decay of any single nucleus is not a predictable event.

2. **Populations of nuclei**

    a. However, decay in a population of radioactive nuclei i.e. in large quantities of a radioactive element is both extremely predictable and characteristic of that element. The term "population" is used in the statistical sense of a very large number of the species, such that its behaviour encompasses that of all smaller numbers or "samples" of the species. In effect it overrides the stochastic variations of the individuals of which the population is composed.

b. The number of radioactive nuclei in a population which decays during an interval of time is proportional to the number of radioactive nuclei present in the instant before each decay event. Decay in a population is therefore an exponential decline with respect to time.

3. **Characteristics of the phenomenon**

   a. The process of decay of an individual radioactive nucleus is homogeneous through time, and hence space. It has always been the same everywhere.

   b. The rate of the process depends only on the nature of the radioactive element.

   c. As far as we are aware, no other natural phenomenon affects the probability of decay of an individual nucleus. It is not influenced by temperature, pressure or gravity etc. In particular, it is not affected by acceleration, or by velocity in the way that mass is predicted to be affected in the Theory of Relativity.

C. Time Dilation

The Theory of Relativity predicts time dilation which becomes apparent as the speed of light is approached. Units of elapsed time, conventionally seconds, are predicted to become longer as velocity increases. This is accompanied by changes in all the parameters which form the framework of physics: length, mass and everything derived from them.

If time dilation occurred with radioactive decay, it could only mean that the interval between events or sparks increased with the velocity of radioactive material. This would raise a fundamental question, which could be asked in various forms as follows:

1. How could a nucleus know about the time interval between its own decay and that of its neighbours, since there is no interaction between them?

2. How could time dilation be reconciled with a process which is measurably a sequence of stochastic events? The sparks themselves are the events. If the interval between events occurring in the mass is dilated, by what principle can this occur?

3. If in spite of these objections time is still considered to be dilated in radioactive decay, what exactly does this mean, since “time is nothing without an event to mark it” (Einstein), and there are no events between sparks ?

D. Radioactive Clock

The first problem in devising a clock is to establish a standard of radioactive decay. A radioactive isotope should be selected which decays slowly enough to count the sparks with the required accuracy, but fast enough to reach a conclusion in an acceptable time. The isotope should give off radiation which is unambiguous to measure, so probably a single species, and easiest to count. It depends on what detectors are available or can be developed with the required accuracy.

Such a standard would be the basis of measuring time in terms of the number of sparks which occur in a radioactive element, and involves no other natural phenomena at all. Number is unambiguously the same everywhere at all times, which is what is required.

1. Preparation

a. Take a substantial homogeneous mass of the selected radioactive element. Such a mass would contain a very large population of radioactive nuclei, such that many samples can be drawn from it which have identical decay curves, except that they would start with smaller numbers of nuclei.

b. Divide the mass into a large number of aliquots of equal mass. Each aliquot then contains identical populations of radioactive nuclei i.e. equal numbers.

c. Shield each aliquot from inputs arising from extraneous sources, so that the only process going on inside each box is decay of the radioactive material which it contains i.e. there should be no radiation from outside which can generate new radioactive nuclei and so introduce confusion. Nor should the sparks emitted give rise to other radioactive species which would cause competing reactions and confuse measurement.

2. Process

Count the number of sparks in each aliquot as they all decay in parallel. Count them in such a way as to avoid any uncertainty arising from the introduction of influences external to the decay process i.e. the detector should not introduce uncertainties about the meaning of the count.

The number of sparks will never be identical for all aliquots, because these are discrete events and they occur stochastically, and so the chances of all aliquots producing a spark simultaneously are effectively zero.

However, as decay proceeds, the spark counts for all aliquots increase in parallel to the point at which the differences between them in relation to the total count become vanishingly small. Before this level is reached, a point will occur at which the difference between them is, say, 1 in 10^{10} sparks. This could in effect be deemed the required accuracy of the clock, though of course any other number could be chosen. It depends how patient one is prepared to be.

Suppose the required accuracy has been reached at an average count of N_1 per aliquot. Beyond this point no difference will be detected between the aliquots within the required limits of accuracy, which proves the validity of the initial subdivision. If the aliquots had been too small, the numbers of radioactive nuclei in each would have been too small, and significant imbalances in the numbers of sparks would have persisted, simply on the basis of probability distributions. The aliquots would have been statistical samples, that is approximations of the whole quantity from which they were drawn, rather than parallel populations.

The unit interval of "radioactive time" is then defined by the number N_1. This number marks the time which elapsed from the beginning of measurement up to the decay of the N_1 th nucleus under standard conditions i.e. a standard aliquot of the standard radioactive element with a standard level of radioactivity. The number N_1 under these conditions is the absolute unit interval of time, since it has the same value and will always represent the same elapsed time everywhere.

3. Procedures

From this point there are two different procedures which could be used.

a. Single absolute unit interval of time

The absolute unit of time could be used as a yardstick with the proviso that it could not be subdivided, partly because it is exponential, and partly because using a fraction would take the measurement below the threshold of accuracy and make the procedure pointless.

The unit would be used by running the clock in parallel with a different clock, say a caesium clock, and noting how many caesium seconds it took from the start of measurement to reach N_1 sparks. This would compare the absolute unit with the second defined in electromagnetic terms, though there is no reason why they should be anything like comparable in the interval of time each measures.

The difference would be that the absolute unit would represent the same interval of time anywhere in the Universe at any time, whereas the caesium second would represent an interval of time which was characteristic of its time and place.

It might be a very large place i.e. the whole Earth, stationary at ground level, though there might be differences between atomic clocks which are not entirely caused by the apparatus, and necessitate averaging of atomic clocks, as currently practised. It might not be true, say, at satellite height above the Earth.

It might also be true for a very long time period, except in geological or astronomical terms.

But it is to detect such differences and their causes, or to confirm that they do not exist, that the absolute unit of time needs to be defined.

b. Successive absolute unit intervals of time

The alternative to stopping the count at N_1 is to keep going. Counting could continue until the limits of the detector were reached, or to the point at which the number of sparks fell below the required population and caused erratic counts for successive units of time. If the count continued for *n* units of time, the number of sparks which defined consecutive units could be calculated from the decay curve, as in the Figure.

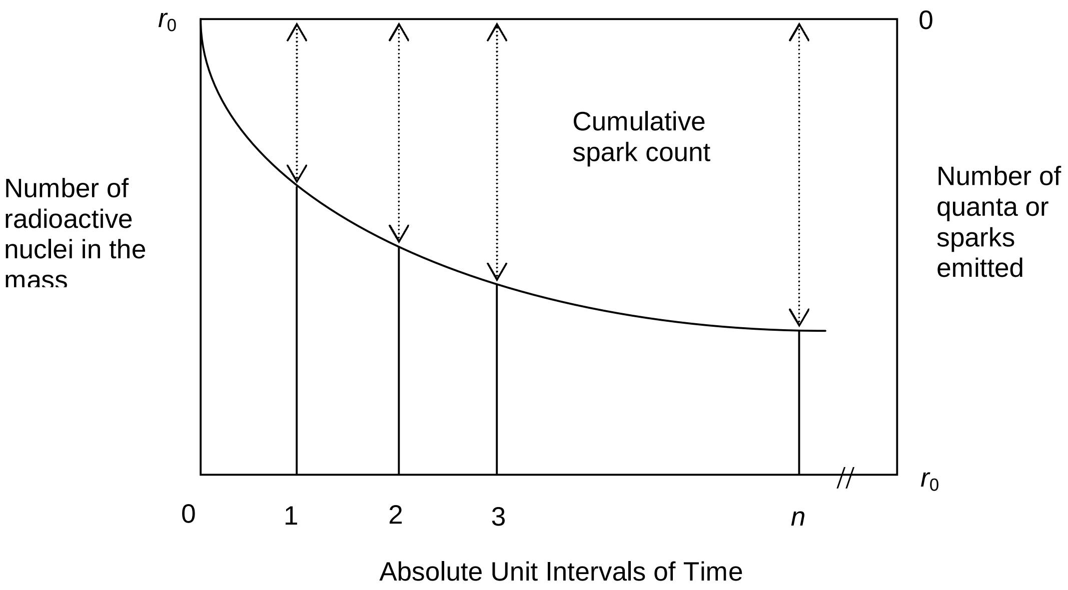

Figure. Decay of Radioactive Element and Increase in Spark Count with Absolute Unit Intervals of Time

The equation for radioactive decay is an exponential of the form:

$$y = ke^{-\lambda t}$$

The equation as used here relates to the decrease in the number of radioactive nuclei over time, not the change in the number of sparks per second on a conventional clock, because this would involve another natural phenomenon, which is what we are trying to avoid.

The fundamental principle is that the decay of radioactive nuclei is exponential on any base of time, however measured, because both the phenomenon and the mathematics are homogeneous through time.

If the number of radioactive atoms present initially is r_0, then the number of radioactive atoms r_t present at any time t during the decay is given by the equation:

$$r_t = r_0 e^{-\lambda t}$$

Thus after 1 unit of elapsed time, measured in any units from the start of the process, the number of radioactive atoms decreases from r_0 to r_1, where

$$r_1 = r_0 e^{-\lambda}$$

Calculation of λ

By rearrangement of the above equation we see that

$$\frac{r_1}{r_0} = e^{-\lambda}$$

and

$$-\lambda = \ln\left(\frac{r_1}{r_0}\right)$$

The number of radioactive atoms which has decayed during the first unit of elapsed time is $r_0 - r_1$. This is identical to the number of sparks emitted during this period, which by the process described above for the single absolute unit of time we have designated N_1. Thus

$$r_0 - r_1 = N_1$$

and

$$r_1 = r_0 - N_1$$

Then by substitution,

$$-\lambda = \ln\left(\frac{r_0 - N_1}{r_0}\right)$$

or

$$-\lambda = \ln(r_0 - N_1) - \ln(r_0)$$

from which

$$\lambda = \ln(r_0) - \ln(r_0 - N_1)$$

Hence

$$\lambda = \ln\left(\frac{r_0}{(r_0 - N_1)}\right)$$

The parameter λ is the natural logarithm of the ratio of the original number of radioactive nuclei r_0 to the number remaining after the decay of N_1 nuclei i.e. $(r_0 - N_1)$.

From this equation λ can be calculated if N_1 and r_0 are known.

N_1 has been counted by the procedure described above. The accuracy of λ will depend on how accurately the initial number of radioactive atoms r_0 is known. This may require some extremely accurate weighing, for instance, but it need be done only once for a particular radioactive element, because when λ is known with sufficient accuracy it applies to radioactive decay at all times.

The parameter λ is a form of radioactive decay constant on the base of the absolute unit of time, an 'absolute radioactive decay constant' for the element concerned.

Calculation for successive time periods

During the first absolute unit of time, the number of radioactive atoms which has decayed is $r_0 - r_1$, which we have designated N_1. Therefore

$$N_1 = r_0 - r_0 e^{-\lambda}$$

$$= r_0\left(1 - e^{-\lambda}\right)$$

During the second absolute unit of time, which is consecutive with the first, the number of radioactive atoms which decay is $r_1 - r_2$ where

$$r_1 = r_0 e^{-\lambda}$$

and

$$r_2 = r_0 e^{-2\lambda}$$

Hence

$$r_1 - r_2 = r_0 e^{-\lambda} - r_0 e^{-2\lambda}$$

$$= r_0\left(e^{-\lambda} - e^{-2\lambda}\right)$$

$$= r_0 e^{-\lambda}\left(1 - e^{-\lambda}\right)$$

But from the equation above

$$r_0\left(1-e^{-\lambda}\right)=N_1$$

Therefore

$$r_1-r_2=N_1e^{-\lambda}$$

The number of radioactive atoms which decayed during the consecutive second absolute unit of time is therefore

$$N_1e^{-\lambda}$$

Since this is identical to the number of sparks which occurred during the period, the length of the second absolute unit of time in this series can be measured by measuring the number of sparks.

During the third absolute unit of time, which is consecutive with the second, the number of radioactive atoms which decay is $r_2 - r_3$ where

$$r_2=r_0e^{-2\lambda}$$

and

$$r_3=r_0e^{-3\lambda}$$

Hence

$$r_2-r_3=r_0e^{-2\lambda}-r_0e^{-3\lambda}$$

$$=r_0\left(e^{-2\lambda}-r_0e^{-3\lambda}\right)$$

$$=r_0e^{-2\lambda}\left(1-e^{-\lambda}\right)$$

But from the equation above

$$r_0\left(1-e^{-\lambda}\right)=N_1$$

Therefore

$$r_2-r_3=N_1e^{-2\lambda}$$

The number of radioactive atoms which decayed during the consecutive third absolute unit of time is therefore

$$N_1e^{-2\lambda}$$

Since this is identical to the number of sparks which occurred during the period, the length of the third absolute unit of time in this series can be measured by measuring the number of sparks.

To generalise, during the *n*th absolute unit of time, which is consecutive with the (*n*-1)th unit, the number of radioactive atoms which decay is

$$r_{n-1} - r_n$$

where

$$r_{n-1} = r_0 e^{-(n-1)\lambda}$$

and

$$r_n = r_0 e^{-n\lambda}$$

Hence

$$r_{n-1} - r_n = r_0 e^{-(n-1)\lambda} - r_0 e^{-n\lambda}$$

$$= r_0 \left(e^{-(n-1)\lambda} - e^{-n\lambda} \right)$$

$$= r_0 e^{-(n-1)\lambda} \left(1 - e^{-\lambda} \right)$$

But from the equation above

$$r_0 \left(1 - e^{-\lambda} \right) = N_1$$

Therefore

$$r_{n-1} - r_n = N_1 e^{-(n-1)\lambda}$$

The number of radioactive atoms which decayed during the *n*th consecutive absolute unit of time is therefore

$$N_1 e^{-(n-1)\lambda}$$

As before, the length of the *n*th absolute unit of time in this series can be measured by measuring the number of sparks. This is summarised in the Table.

Cumulative spark count

The cumulative total of sparks emitted during the decay process is the sum of the sparks measured in the individual periods. Thus:

- the 1st absolute unit of time ends when the spark count reaches N_1 (definition).

– the 2nd absolute unit of time ends when the spark count for the unit reaches

$$N_1 e^{-\lambda}$$

which is a cumulative total of

$$N_1 + N_1 e^{-\lambda} = N_1\left(1 + e^{-\lambda}\right)$$

Absolute Units of Time Number	Length of the Numbered Absolute Unit of Time in Numbers of Sparks	Cumulative Spark Count at End of the Numbered Absolute Unit of Time
1	N_1	N_1
2	$N_1 e^{-\lambda}$	$N_1\left(1 + e^{-\lambda}\right)$
3	$N_1 e^{-2\lambda}$	$N_1\left(1 + e^{-\lambda} + e^{-2\lambda}\right)$
…	…	…
…	…	…
n	$N_1 e^{-(n-1)\lambda}$	$N_1\left(1 + e^{-\lambda} + e^{-2\lambda} + ... + e^{-(n-1)\lambda}\right)$

Table. Increase in Spark Count with Absolute Units of Time

– the 3rd absolute unit of time ends when the spark count for the unit reaches

$$N_1 e^{-2\lambda}$$

which is a cumulative total of

$$N_1 + N_1 e^{-\lambda} + N_1 e^{-2\lambda} = N_1\left(1 + e^{-\lambda} + e^{-2\lambda}\right)$$

– the *n*th absolute unit of time ends when the spark count for the unit reaches

$$N_1 e^{-(n-1)\lambda}$$

which by analogy is a cumulative total of

$$N_1 + N_1 e^{-\lambda} + N_1 e^{-2\lambda} + ... + N_1 e^{-(n-1)\lambda} = N_1\left(1 + e^{-\lambda} + e^{-2\lambda} + ... + e^{-(n-1)\lambda}\right)$$

A caesium clock could be run in parallel with the radioactive clock during the *n* absolute units of elapsed time. If the caesium clock recorded this as *x* seconds, then

n absolute units of time = x caesium seconds

or

1 *absolute unit of time = x/n caesium seconds*

at that particular time and place. If that ratio varied, it must be because the caesium unit of time had changed under the influence of the environment in which the comparison was made. This would be influencing either the period of vibration of the caesium atom itself, or, which seems more likely, the electromagnetic radiation after it had left the atom i.e. in space.

There must be doubt whether any such variation, if detected, could be considered as time dilation. Since time applies to both types of clock it would certainly not provide confirmation of the Theory of Relativity, whatever its cause.

E. Confounding of Units of Time and Length

The danger of using wavelengths of electromagnetic radiation to define both the second and the metre was raised by Clemence in the mid 1950s when they were first proposed as standards. His objection was that units of length and of time would lose their independence, and he urged frequent comparison between the new units and the physical metre and astronomical second (1).

However, it is in fact more complex than that, because units of length and time defined in terms of wavelength would become confounded in the statistical sense. They would both be influenced by some external factor which was characteristic of the particular time and place.

The effects on each would not necessarily be proportional, in which case recalibrating one variable against a physical standard would not solve the problem with the other. Recalibrating both would not solve the problem either, because it would still leave them varying simultaneously even if only one were changed, as they were applied in environments which were different from the standard in which they were compared.

In short, time and length expressed in terms of wavelengths would no longer be orthogonal. There would always be three variables in any situation: time, distance and a time-distance interaction which depended on the environment. The third variable itself would not be possible to control independently, because the only variables to hand are time and length, and any measurement of either would contain an unknown component in the form of the interaction.

Moreover all variables derived from them would be similarly affected: velocity, acceleration, force etc. The interaction, if it exists, might be very small, but it would be extremely significant.

None of these problems arise with physical standards, of course, but wavelength-based units are much more convenient and precise in practical situations, which is why the translation was originally made.

The measurement of time by the sort of radioactive clock described here could not become confounded with any other parameter or phenomenon. Hence the term "absolute" unit of time.

F. Relativity

Various experiments have been carried out over the years to detect time dilation as predicted by the Theory of Relativity. In the mid 1950s four caesium beam clocks were flown around the world, and their timekeeping was compared with a fixed standard in the laboratory. Small but definite changes were detected (2).

The clocks flown in the same sense as the rotation of the Earth ran slower than the standard, and those flown in the opposite sense ran faster, which was in accordance with the predictions of Relativity. The changes were considered to consist of the sum of two components, one caused by the Relativity effect, and the other of equal magnitude caused by gravitational red shift, as also predicted by Einstein.

If it were shown that such changes also occurred in radioactive clocks flown in parallel with caesium clocks, this would be consistent with the Theory of Relativity. However, if they differed in their behaviour, doubt would be cast not on whether the clocks gained or lost time, but on whether this was really time dilation. This could mean some environmental effect either on the caesium atoms or on the electromagnetic wave after it had left the atom i.e. it could be velocity or it could be distance travelled through space with or against the spin of the Earth, as I have proposed elsewhere (3). It could not be variation of the radioactive clock, since radioactive decay is not influenced by any of these things.

The same reasoning applies to the SI unit of length as measured by krypton emissions.

In one reported experiment from the same period carried out by H. J. Hay at Harwell "two radioactive clocks" were placed on a rotating disc, one at the centre and the other on the rim. The idea was to simulate the rotation of the Earth with one Observer stationary at the North Pole and another moving on the Equator to show that they aged differently. The experiment was said to have become possible only when time had become measurable to a thousand millionth of a second (4).

The result was that the "radioactive clock" on the rim "kept time more slowly" than the one at the centre. This was said to confirm time dilation. However the question must be asked whether the sample at the rim did in fact "age" more slowly, whatever that means, or whether it was not simply that the clock, which depended on the measurement of wavelength, ticked a little more slowly in the environment of the experiment.

All sorts of extremely small effects have been attributed to the time dilation predicted by the Theory of Relativity. One which is definite and of great practical importance is that the clocks on the satellites used in the Ground Positioning System (GPS) run on a slightly different time from those on Earth.

The same questions arise. Is it because of time dilation? Or is it because of some interaction with the physical phenomena of the environment? Is it because they are travelling further through space than clocks on Earth?

A clock based on radioactive decay would in principle help to settle the question of time dilation, confirm the SI units of time and length, or otherwise, and provide a means to investigate the influence of different phenomena such as gravity etc on the wavelength of light both in the laboratory and in space.

A. C. Sturt

Guildford Surrey 30 July 2003

References

1. Definition of the Second of Time, G. M. Clemence, NATURE Vol. 176 p1230 December 24 1955.

2. Around –the-World Atomic Clocks J. C. Hafele and Richard E. Keating SCIENCE Vol. 177 pp 166-170.

3. The Timeless Universe II. Redshift Reinterpreted A. C. Sturt 27 September 2001 http://www.churingapublishing.com/timeless_13.htm.

4. The Ascent of Man, J. Bronowski, published by the British Broadcasting Corporation 1973 reprinted 1974 p 255.